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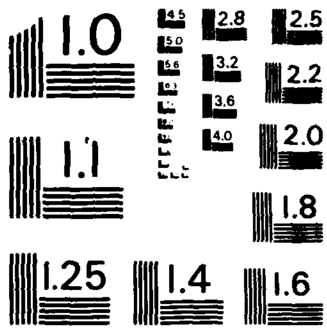

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PRELIMINARY INVESTIGATION OF THE SYSTEMATIC APPROACH TO
THE REPAIR VERSUS REPLACEMENT DECISION-MAKING PROCESS
FOR DETERIORATED CONCRETE BRIDGE DECKS

by

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Concrete bridge deck deterioration, which manifests itself in the form of cracking, scaling and spalling, is a major problem for the state transportation agencies. This deck deterioration accounts for a large portion of the number of the nation's structurally deficient bridges. There is a dilemma over repair versus replacement strategies for those decks in the grey zone (deck condition code 4-6). Thus, the purpose

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systematic approach to the decision-making process. performance and cost characteristics of bridge deck repair and replacement alternatives, components of the decision-making process, technical methodology for implementing decision-making process, needs analysis, economic and fiscal evaluation, technical evaluation, decision-making criteria and constraints, project prioritization, bridge program development.

20.

of this thesis is to provide a preliminary investigation into the systematic approach to the repair versus replacement decision-making process for deteriorated concrete decks.

The existing decision-making process is characterized by a piecemeal synthesis oriented towards emphasizing the advantages of one repair or replacement alternative and ignoring a cost-effective comparison of all possible alternatives.

In the development of the thesis topic, the components or general framework of the decision-making process and the logical steps or technological methodology for process implementation are explored. The performance and cost characteristics of the various repair and replacement alternatives will be discussed extensively. Additionally, the various components of the process (objective, data-base, decision-making criteria and constraints, and methodology) will be linked to the implementation steps: a needs analysis, a technical, economic and fiscal evaluation of competing alternatives, project prioritization, and program development.

PRELIMINARY INVESTIGATION OF THE SYSTEMATIC APPROACH TO THE REPAIR VERSUS REPLACEMENT DECISION-MAKING PROCESS FOR DETERIORATED CONCRETE BRIDGE DECKS

by

MAJOR CHARLES WILLIAM PROTASIO

Submitted to the Department of Civil Engineering on June 26, 1986 in partial fulfillment of the requirements for the degrees of Civil Engineer and Master of Science in Civil Engineering.

ABSTRACT

Concrete bridge deck deterioration, especially premature deterioration, is a major problem for the state transportation agencies throughout the United States. Moreover, this deck deterioration, which manifests itself in the form of cracking, scaling and spalling, accounts for a large portion of the number of the nation's structurally deficient bridges. In particular, the New England states have expressed concern over the dilemma of repair versus replacement strategies for those decks in the grey zone (deck condition code 4-6). Thus, the purpose of this thesis is to provide a preliminary investigation into the systematic approach to the repair versus replacement decision-making process for deteriorated concrete decks.

For a large number of states, the existing decision-making process is characterized by a piecemeal synthesis oriented towards emphasizing the advantages of one repair or replacement alternative and underestimating its disadvantages. An actual cost-effective comparison of all possible alternatives is not routinely undertaken.

In the development of the thesis topic, the components or general framework of the decision-making process and the logical steps or technological methodology for process implementation are explored. The performance and cost characteristics of the various repair and replacement alternatives will be discussed extensively. Additionally, the various components of the process (objective, data-base, decision-making criteria and constraints, and methodology) will be linked to the implementation steps: a needs analysis, a technical, economic and fiscal evaluation of competing alternatives, project prioritization, and program development.

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CHAPTER ONE

INTRODUCTION

1.1 OVERVIEW OF THE IMMENSITY OF THE CONCRETE BRIDGE DECK DETERIORATION PROBLEM

Concrete bridge deck deterioration, especially premature deterioration, is a major problem for transportation agencies throughout the United States! Decks that were once expected to provide relatively maintenance-free service for at least forty years are deteriorating much sooner. In more than 75 percent of the states, only about 10 percent of the federal-aid bridges were built with a deck protection system (105). Moreover, the Federal Highway Administration (FHWA) has discovered that some unprotected decks require major maintenance after only 5 to 10 years of service and must often be replaced after only 15 years of service (12). The immensity of the problem is both staggering in its extent and the associated cost. In 1975, the Federal Highway Administration (FHWA) calculated the cost of bridge deck rehabilitation in the United States at $200 million per year (13). In 1977, the FHWA reported that 65,507 bridges (about 10 percent of the nation's bridges) had badly deteriorated decks (13). During the winter of 1976-1977, The Road Information Program (TRIP) indicated that 1626 bridges were rendered unusable, primarily due to spalling (13). The rehabilitation/replacement cost for these bridges alone was placed at approximately $1 billion. By 1977, an Environmental Protection Agency (EPA)

study estimated the annual damage to bridge decks at $500 million (13). In 1979, the General Accounting Office (GAO) reported to Congress that the total cost to repair the nation's bridge decks had grown to $6.3 billion (109). Thus, the magnitude of bridge deck deterioration is immense.

Currently, 236,000 bridges (approximately 41 percent of the nation's 574,100 bridges) in the National Bridge Inventory (NBI) are eligible for federal Highway Bridge Replacement and Rehabilitation Program (HBRRP) funding as a result of structural deficiencies or functional obsolescence (29). The most recent estimate of the overall cost (Table 1-1) to rehabilitate or replace deficient bridges is approximately $50 billion, and a significant portion of this estimated cost involves correcting deck deterioration (29). Statistically, the deterioration of bridge decks is one of the leading contributors to the number of deficient bridges in the United States (Table 1-2). As a result, much of the bridge rehabilitation efforts have focused on correcting bridge deck deterioration (Table 1-3) and thus constitute a very large repair capital outlay. Nevertheless, the percentage of deficient bridges has either increased or remained constant since the inception of the NBI database. In the Northeast, the factors of intense use, frequency of overloads, extensive application of deicing salts, inadequate design and construction practices, lack of periodic maintenance, and advancing age of the bridge population are underlying factors for this

TABLE 1-1

ESTIMATE TO REPLACE OR REHABILITATE DEFICIENT BRIDGES (29)

COSTS INCLUDE FEDERAL AND STATE SHARES

(FHWA - 1985)

SYSTEM	BRIDGES ELIGIBLE FOR REPLACEMENT OR REHABILITATION (SUFFICIENCY RATING < 50)	ESTIMATED REPLACEMENT COST (IN BILLIONS)	BRIDGES ELIGIBLE FOR REPLACEMENT OR REHABILITATION (SUFFICIENCY RATING < 50-80)	ESTIMATED REHABILITATION COST (IN BILLIONS)
INTERSTATE	540	$ 0.4	3,698	$ 2.1
PRIMARY	8,070	6.6	12,403	4.8
SECONDARY	13,934	4.8	14,921	2.1
URBAN	4,302	4.3	4,968	2.2
TOTAL	26,846	16.1	35,990	11.2
OFF-SYSTEM	120,164	17.2	53,015	3.8
TOTAL	147,010	$ 33.3	89,005	$ 15.0

TABLE 1-2

BREAKDOWN OF STRUCTURALLY DEFICIENT BRIDGES - 1984 (29)

SYSTEM	DECK	SUPER-STRUCTURE	SUB STRUCTURE	CULVERT	OVERALL STRUCTURAL CONDITION	WATERWAY ADEQUACY	MULTIPLE DEFICIENCIES
INTERSTATE	1,370	201	360	33	36	20	754
PRIMARY	2,271	1,095	1,701	164	605	135	4,380
SECONDARY	1,326	1,258	2,018	166	1,964	323	7,435
URBAN	986	705	666	53	296	30	3,038
TOTAL FEDERAL-AID	5,953	3,259	4,745	416	2,901	508	15,607
OFF-SYSTEM	4,620	8,891	9,456	536	25,540	1,524	56,852
TOTAL	10,573	12,150	14,201	952	28,441	2,032	72,459

TABLE 1-3

Breakdown of Improved Bridges -1984 (29)

Highway System	Deck	Super Structure	Sub Structure	Culvert	Structural Condition	Waterway Adequacy
Interstate	207	66	112	20	17	1
Primary	579	424	492	22	175	13
Secondary	630	716	661	20	542	61
Urban	194	167	124	12	96	0
TOTAL FEDERAL-AID	1610	1373	1389	74	820	78
OFF-SYSTEM	2336	3284	2458	77	3656	320
TOTAL	3946	4657	3847	151	4476	398

lack of improvement (70,87). As a result of primarily these factors, a 1980 study of the infrastructures in New York state indicated that the current rate of decay is five times as large as the historical rate (31). In the future, the need for rehabilitating or replacing bridge decks is expected to increase simply as a result of the advancing age of the bridge population. Although the useful life of the average highway bridge is approximately 50 years, over 40 percent of the nation's bridges are over 40 years old (Figure 1-1). Consequently, despite the use of federal, state and local funds to improve 10,605 bridge structures in 1984, an additional 16,400 bridges in the National Bridge Inventory were reclassified as structurally deficient (29). Of the 16,400 newly-classified, structurally deficient bridges, 53 percent of the on-system bridges (3,250) and 58 percent of the off-system bridges (6,014) are more than 40 years old. Additionally, 19 percent of the on-system bridges (1,158) and 50 percent of the off-system bridges (5,155) were posted or closed. These 16,400 bridges represented an increase from the previous year of 8 percent on the Federal-aid system bridges and 2 percent on the off-system bridges (29). Thus, deterioration of bridges and bridge decks continues to take place at a rate faster than that which repairs are affected.

1.2 BRIDGE DECK DETERIORATION MECHANISMS AND CONDITION ASSESSMENT TECHNIQUES

In order to implement an effective deck repair/replace-

FIGURE 1-1 Age Distribution Of American Bridges

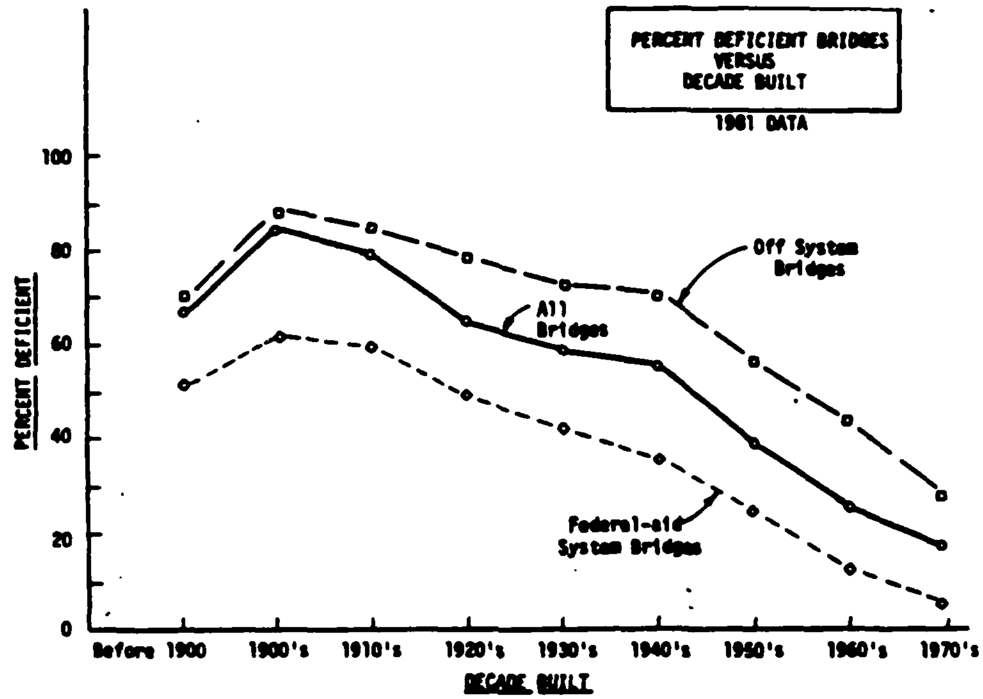
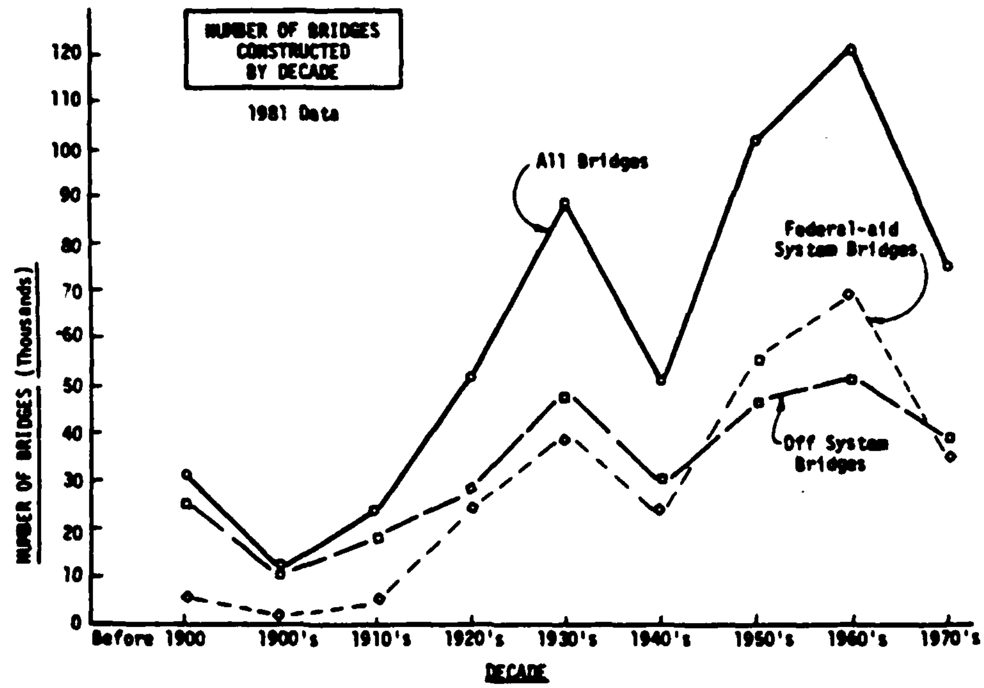


FIGURE 2



ment program, an understanding of the bridge deck deterioration mechanisms and the current, deck condition assessment techniques is essential. Thus, the early chapters of this thesis will focus on the prevailing knowledge regarding these subjects and, then, how this knowledge impacts on the systematic, decision-making process related to deck repair versus replacement strategies. Bridge deck deterioration manifests itself in the form of cracking, scaling, wear and polishing, and spalling (26). Although defects in materials, inferior worksmanship, and frost action have influenced bridge deck deterioration, the primary problem is the corrosion of the reinforcing steel and the spalling that then occurs (105). This corrosion is more likely to occur under the conditions of high concrete permeability, high chloride concentrations, inadequate concrete cover, high water-cement ratios, and insufficient consolidation (6). Undoubtedly, the increased frequency of spalling is directly related to the heavy application of deicing salts, NaCl and $CaCl_2$. In 1947, less than 0.5 million tons of salt were applied to American highways. During the mid 1970's, many state highway agencies adhered to an "all-weather bare pavement" policy, resulting in the application of 12 million tons of road salt/year (13). These salts (or chloride ions), in the presence of oxygen and moisture, initiate corrosion of the embedded reinforcing steel and causes expansive tensile forces to be exerted on the overlying concrete (6,105).

The current methods of assessing bridge deck condition are essentially based on measuring those mechanisms and parameters associated with deterioration. As an example, the importance of chloride ions in the corrosion of reinforcing steel and subsequent spalling has prompted measurements of chloride content. The current and most widely used methods of assessing bridge deck condition include:

- visual inspection,
- delamination detection using "sounding" techniques,
- petrographic examination of cored specimens,
- measurement of the chloride content at the level of the top reinforcing mat,
- determination of the depth of the top reinforcement,
- determination of galvanic corrosion cell electrical potentials (corrosion potential), and
- determination of the permeability of the bridge deck seals and membranes using electrical resistance testing.

An understanding of the effectiveness, advantages and limitations of these methods provide a framework for formulating repair/replacement strategies. The condition assessment of the decks define the extent of the deterioration problem, the allowable repair or replacement alternatives, and the priorities of the various projects. Thus, an understanding of both concrete deterioration mechanisms and the current deck-condition assessment techniques is essential to resolving the deck repair versus replacement dilemma.

1.3 CONCERNS OF THE NEW ENGLAND SURFACE TRANSPORTATION INFRASTRUCTURE CONSORTIUM

The five New England States of Maine, Massachusetts, Vermont, Rhode Island and New Hampshire have all indicated a concern about the management of their bridge deck rehabilitation/replacement programs. Together, these states have 13,262 bridges listed in the National Bridge Inventory Bridge and have identified a total of 5,274 structurally deficient or functionally obsolete bridges (Table 1-4). Moreover, approximately 16 percent of these total bridges can be grouped into deck condition categories of critical or poor (deck code 0-4) and thus require immediate rehabilitation or replacement efforts (104). An additional 13% of these total bridges are classified in the deck condition category of fair (deck code 5) and thus will need repair or replacement within the near future (104). Moreover, the estimated cost of satisfying the immediate deck rehabilitation or replacement needs in these five New England states is a staggering $366M. Obviously, there are fiscal constraints to the expenditure of such massive sums. For instance, Vermont is scheduled to spend $6 million to repair or replace deteriorated bridge decks during the 1986 time frame (99). Moreover, all states have experienced difficulty in correctly identifying the cost of individual deck projects (98-103). In some isolated but extremely important and costly instances, the estimated extent of deck deterioration is significantly lower than the actual deterioration when the bridge deck is actually opened for

TABLE 1-4

BRIDGE STATUS OF NEW ENGLAND STATES

AS OF DECEMBER 31, 1984 (29)

	Bridges on Federal-aid System	Structurally Deficient	Functionally Obsolete	Deficient Bridges
MAINE	1257	127	80	207
MASSACHUSETTS	3597	880	48	928
NEW HAMPSHIRE	1202	168	159	327
RHODE ISLAND	563	76	19	95
VERMONT	1289	145	307	452
TOTAL	7908	1396	613	2009

	Bridges Off Federal-aid System	Structurally Deficient	Functionally Obsolete	Deficient Bridges
MAINE	1335	310	287	597
MASSACHUSETTS	1179	631	33	664
NEW HAMPSHIRE	1349	422	582	1004
RHODE ISLAND	126	33	14	47
VERMONT	1365	306	647	953
TOTAL	5354	1702	1563	3265

rehabilitation (98-103). Such occurrences necessitate the request for additional funds, which ultimately impact upon funding for other projects.

Inherently, there is great uncertainty concerning the procedures and reliability of current deterioration detection techniques. The validity of the criteria for interpeting inspection results, especially when conflicts between different testing methods occurs, is another area of major concern. Currently, many of the states are relying too heavily upon a limited number of inspection methods. As an example, Maine relies almost soley on chloride content tests, regarding electrical potential tests as ineffective (103). However, Vermont places the primary emphasis on these electrical potential tests and much lesser emphasis on chloride content testing (99). The general consensus of the New England states is that more meaningful information as to the true nature of the bridge deck condition is needed. This may involve clarification of the procedures, criteria, and interpretation of the current testing methods. But probably, the development of new and rapid nondestructive testing techniques, such as infrared thermography and ground-penetrating radar, also must occur. In particular, ground-penetrating radar offers a great potential for a variety of significant measurements: the location and orientation of the reinforcing steel, the cover depth of the concrete to the top mat of reinforcing steel, the water content, the chloride content, and the location of delaminated areas. These deck assessment

techniques will be addressed in future research as part of a New England Surface Transportation Infrastructure Consortium, consisting of state transportation agencies, state universities, and the Massachusetts Institute of Technology.

1.4 RESEARCH OBJECTIVE AND OUTLINE

Although the research into improving deck condition assessment is essential, the judicious use of this data as part of a decision-making process is imperative. Typically, state transportation agencies have had little difficulty in identifying repair or replacement strategies for those bridge decks whose condition is readily apparent. Accordingly, for bridges that are relatively new and/or exhibit little deterioration (deck condition code 7-9), a rehabilitation strategy is commonly utilized. Likewise, for those decks that are highly deteriorated (deck condition code 1-3), a replacement strategy is likely to occur. Thus, another major area of concern expressed by the New England state transportation agencies was the dilemma of repair versus replacement strategies associated with bridge decks in the grey zone (a deck condition code of 4-6). Currently, the existing decision-making process is characterized by a piecemeal synthesis of incomplete or inaccurate information. This piecemeal synthesis has, in general, been oriented toward emphasizing certain advantages of one alternative and underestimating its disadvantages (42). Moreover, new technological techniques (e.g., cathodic protection) are often ignored or misunderstood (98-

103). An actual cost-effective comparison of all possible alternatives is not routinely undertaken. Too much emphasis on repeating past decisions subsequently occurs. Thus, there is genuine concern to improve the repair versus replacement decision-making process associated with bridge decks in the grey zone.

This problem inherently leads to consideration of the overall systematic approach or framework necessary to formulate a judicious repair or replacement decision. This system for decision making must be a logical, clearly defined, step-by-step procedure. The overall objective of such a systematic approach is to expose all possible bridge deck repair and replacement alternatives, evaluate them on the basis of clearly defined criteria and constraints, and to arrive at an optimal or near optimal solution. The ultimate aim of such a system would be to discover and take into account those elements that truly influence the outcome of an optimal or near optimal solution (76). Initially, this would include identification of bridges for further detailed inspection. Eventually, this complicated process would involve linking various input items with specific decision aides or criteria to achieve an adequate and economically feasible rehabilitation or replacement decision. Thus, the purpose of this thesis is to provide a preliminary study or synthesis of this systematic approach with respect to the deck repair versus replacement dilemma. Specifically, the thesis will establish

the framework or components for establishing a systematic approach to this decision-making process. Additionally, the thesis will provide the technical guidance on the quantitative methods that should be considered in developing this systematic approach.

A key element in this process is a user oriented, up-to-date, complete and orderly structured data-base. This data base will provide the necessary bridge data essential to support the decision-making process. Such a data-base must encompass the following information categories:

- Structural Inventory and Traffic Data,
- Structure Inspection and Appraisal,
- Capacity and Functional Adequacy,
- Maintenance History and Projected Future Needs,
- Environmental and Other Factors, and
- Relevant Details for Rehabilitation and Replacement Techniques (42).

Clearly, the identification and relative importance of specific input items that are associated with these information categories must be ascertained.

As previously mentioned, both the objective and the data-base are only two elements of this overall systematic approach. Another critical element includes the identification of an appropriate and clearly defined criteria for the decision-making process. In this regard, the concepts of functional adequacy for both current and future use and

engineering economics are important. Associated with engineering economics are a variety of factors, to include the planning horizon, discount rates, direct and indirect costs and an appropriate methodology to evaluate the total cost. Ideally, a life-cycle costing model is needed that would reflect the cost-effectiveness of feasible alternative repair or replacement strategies. An eventual evaluation of competing repair and replacement strategies must also consider a variety of constraints. These constraints would include the availability of funds, local and legal constraints, peculiar site conditions, technological limitations, and other factors.

The final and most critical feature of this systematic approach to decision-making is describing the actual methodology that will link the various input elements together for determining the appropriate repair versus replacement strategy formulation. Certainly, it is essential that this overall process has the flexibility to incorporate engineering experience and judgement as well as constraints and criteria. The concept of prioritization of projects must also be addressed within this systemic framework. This methodology provides the logic and intergrated process essential for the decision-making process and the framework for resolving the repair versus replacement dilemma.

In the development of this thesis, a building - block approach to the problem of repair/replacement strategy formu-

lation is used. Accordingly, the early chapters of the thesis both summarize and analyze the previously mentioned input factors and the later chapters link these input elements together via a systematic framework. The results of this research will be described in eight sections. Following this introductory chapter, Chapter Two will summarize the mechanisms and parameters associated with the various forms of concrete bridge deck deterioration. Knowledge of these mechanisms and parameters serve as a basis for interpreting current deck inspection techniques and assessing bridge deck condition, developing new inspection techniques, establishing design standards for new construction and rehabilitation efforts, and identifying critical data-base elements essential for the repair/replacement decion-making process.

Chapter Three outlines the current deck inspection techniques, establishes the role of deck evaluation in the repair/replacement decision-making process, and comments on the potential of infrared thermography and ground penetrating radar techniques. Until these new insitu testing techniques are refined, the measurements, strengths, and weaknesses of the current inspection techniques serve as the primary method of assessing bridge deck condition. Chapter Four examines the key features associated with the National Bridge Inventory (NBI) established by Congress in 1979. The historical origin, purposes, trends, validity of data items, and mandated inspection requirements associated with the NBI are important to understanding the structural and conditional appraisals

currently being conducted by the states. Key data elements of the NBI, as well as additional elements that need to be incorporated into the NBI, that are essential to the repair/ replacement dilemma are identified. Of great significance is an understanding of the Federal Bridge Replacement and Rehabilitation Program that serves as a funding and prioritization method for deteriorated bridge deck rehabilitation.

Chapter Five outlines the various repair and replacement alternatives. The costs, performance characteristics and service life associated with these techniques are examined. This chapter will serve as a basis for the later development of specific decision criteria associated with the appropriateness of each alternative. Chapter Six provides an overall systematic approach to the repair versus replacement decision-making process. Initially, this chapter outlines the general stategic approach to developing state transportation programs and briefly highlights the general concepts associated with an overall bridge management system. Specifically, the chapter identifies the components or the general framework of the systematic repair/replacement decision-making process and formulates the logical steps or technical methodology necessary for implementing this process.

Chapter Seven develops a life-cycle costing technique that can be used to evaluate alternative repair/replacement techniques. The concepts of direct costs, indirect (user costs), planning horizons, interest rates, and service life

are examined. Finally, Chapter Eight provides an overall summary, provides conclusions, and identifies areas of future research.

CHAPTER TWO

CONCRETE DETERIORATION MECHANISMS

2.1 INTRODUCTION

Any discussion with regards to repair/replacement strategies for deteriorated concrete bridge decks must initially focus on the various forms of deterioration (Figure 2-1). Conditions of bridge deck deterioration are commonly identified as cracking, scaling, and spalling. Additionally, wear and polishing are performance features of bridge decks that are important in determining deck service life. An understanding of the essential parameters and mechanisms of deterioration is significant for several reasons:

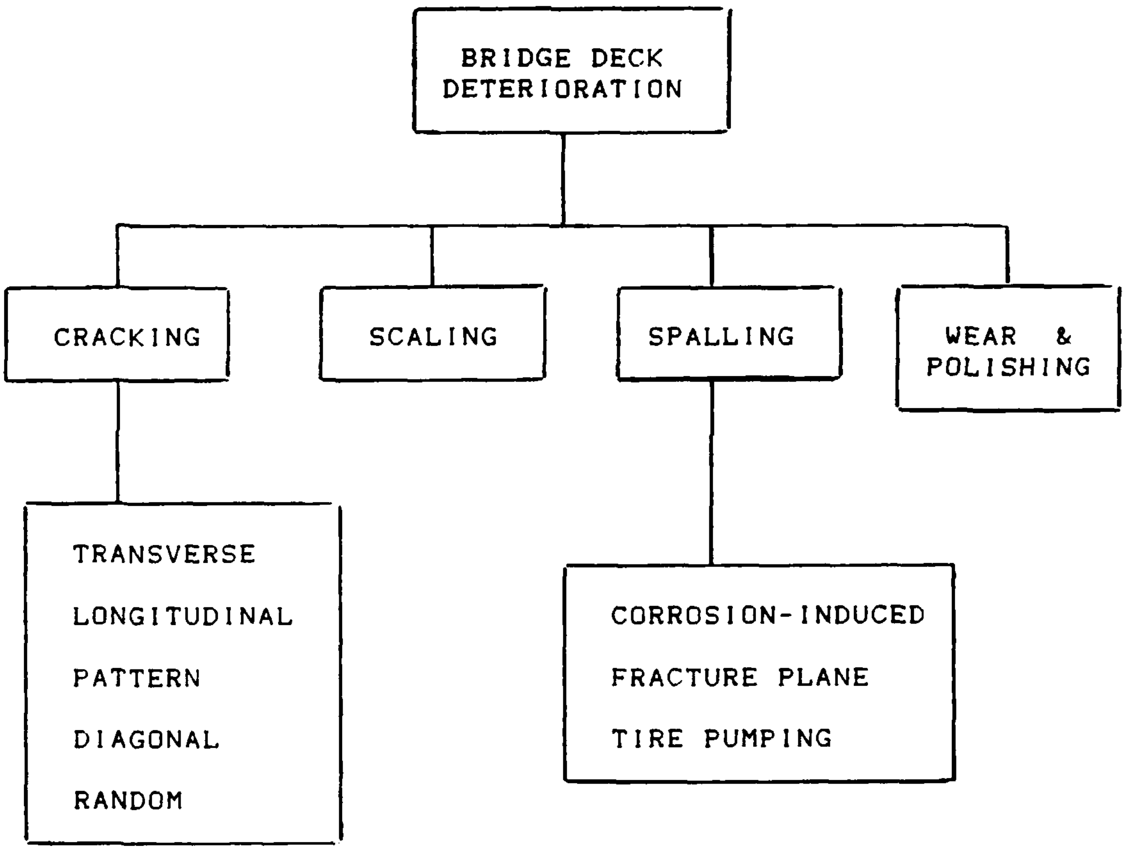
- knowledge of these parameters and mechanisms provide a basis for developing inspection techniques to identify and quantify not only the state of deterioration but those incipient conditions prior to actual deterioration.

- knowledge of these parameters and mechanisms provide a basis for establishing initial construction standards, such as cover depth, water-cement ratio and air-entrainment procedures, and for selecting the appropriate repair/replacement design standards and techniques.

- knowledge of these parameters and mechanisms assist in the identification of critical data-base items that later can be used for inspection scheduling, the choice of inspection techniques, the development of statistical or probability-based models for deterioration, the estimation of the service

FIGURE 2-1

FORMS OF DETERIORATION



life of various rehabilitation or replacement methods, and ultimately the analysis of the cost-effectiveness of such methods.

Thus, this chapter will briefly focus on these various forms of deterioration, identifying the prevailing theories as to their causes and also identifying the factors that impact upon the degree and rate of deterioration.

2.2 CRACKING

One of the first and most common signs of initial deterioration in a bridge deck is cracking. Essentially, cracking is a characteristic of concrete attributable to its low tensile strength, adverse curing conditions, load effects, and the large volumetric changes resulting from humidity and temperature differentials (6,26,105). Normally, cracks are manifested in several forms, including transverse cracks, longitudinal cracks, pattern or map cracks, diagonal cracks, and random cracks (6). Although these various types of cracks may produce a similar deterioration mechanism, the origin of the crack has a significant effect on concrete bridge deck durability (12). Thus, the microcracks that appear immediately following construction, due to shrinkage or settlement of the falsework, do not significantly reduce the concrete strength or adversely affect deck performance. Traditionally, these types of cracks are repaired with a flexible, joint-sealing compound (26). In cases of extensive microcracking which are not feasible to fill with joint-

sealing compounds, an overlay with a waterproof membrane capable of bridging the cracks is currently recommended by the FHWA (26).

Unlike the microcracks, time-dependent cracks and those cracks incurred from structural inadequacies, such as the use of reactive aggregates, may pose serious problems. These cracks intensify with time, may produce fracture planes and access paths for chlorides and moisture, and eventually result in the complete disintegration of the concrete (6,12,105). Among these time-dependent cracks, the transverse crack is the predominant type, accounting for approximately 80% of the total number of crack (6,12). Consequently, this type of cracking will be examined in much greater detail than the other forms of cracking.

2.2.1 TRANSVERSE CRACKS

Transverse cracks appear fairly straight and perpendicular to the roadway centerline and are associated with the primary slab reinforcement (105). Furthermore, these cracks are attributable to volume changes occurring in both plastic and hardened concrete, restraint to subsidence (settlement) of aggregate and cement particles, and adverse conditions during placement (6,12). Such cracks may result from conditions that produce premature set, such as high winds and high temperatures during placement or curing delays (6,16). Transverse cracks also occur if moisture on the deck rapidly

evaporates during the early stages of set. During placement of concrete, aggregate and cement particles settle and displace the mix water to the surface (a self-consolidation process). Obstructions to this process may disrupt uniform settlement and cause transverse cracks. Moreover, volume changes in the hardened concrete, which eventually result in transverse cracks, are manifested in several ways (6,12). Under one scenario, the tendency for concrete to shrink upon drying may be restrained in the slab and thus produce cracks. As a result of inadequate curing procedures, cracks may form due to non-uniform shrinkage stresses throughout the slab thickness. In particular, the slab may have dried primarily and initially from the upper face due to the presence of deck formwork. Consequently, tensile forces may form at the upper face of the slab, producing these non-uniform shrinkage stresses previously alluded to. Under another scenario, thermal effects may result in non-uniform compressive or tensile stresses and an inability to accommodate the resultant volume changes (6). Finally, transverse cracks occur most frequently over the top reinforcement steel, which acts as both a restraint to shrinkage and a source of stress concentration (6,12).

Various studies have revealed certain trends that establish a relationship between transverse cracking and superstructure type. For instance, these cracks are frequently found on continuous bridges rather than simple spans (6). In fact, the lowest incidence of transverse cracking occurred on

prestressed concrete and reinforced concrete simple spans. Also, structural steel spans exhibit slightly greater transverse cracking than reinforced concrete simple spans (6). On reinforced concrete bridge decks, the negative moment areas experience more prominent and more closely spaced transverse cracking than the positive moment areas (119). Additionally, those spans with increasing lengths exhibit a greater probability of transverse cracking (6,12). By increasing the span length, there is a corresponding increase in the effects of live loads, impact, longitudinal flexibility and, in the case of continuous structures, adjacent span loading. Studies have established no certain relationship to transverse cracking and the parameters of age, traffic volume, and the use of stay-in-place forms (a specific construction technique in concrete placement)(6). Finally, air entrainment has been found to have no effect on the occurrence of transverse cracking.

2.2.2 OTHER TYPES OF CRACKING

From an appearance perspective, the remaining types of cracking can be distinguished as follows:

- Longitudinal cracks, which are caused by volume changes, resistance to subsidence and early drying shrinkage, also appear fairly straight but roughly parallel to the roadway centerline (6,12).

- Diagonal cracks, unlike the previously mentioned cracks, are shallow in depth, roughly parallel, and form at

TABLE 2-1

CRACKING MECHANISMS

TRANSVERSE CRACKING	
APPEARANCE:	FAIRLY STRAIGHT AND PERPENDICULAR TO ROADWAY CENTERLINE; FREQUENTLY FORM OVER REINFORCING STEEL
MECHANISMS:	VOLUME CHANGES IN BOTH PLASTIC AND HARDENED CEMENT
	RESTRAINT TO SETTLEMENT OF AGGREGATE AND CEMENT PARTICLES
	ADVERSE CONDITIONS DURING PLACEMENT, SUCH AS HIGH WINDS OR HIGH TEMPERATURE
LONGITUDINAL CRACKING	
APPEARANCE:	FAIRLY STRAIGHT AND ROUGHLY PARALLEL TO ROADWAY CENTERLINE
MECHANISMS:	VOLUME CHANGES
	RESISTANCE TO SUBSIDENCE & EARLY DRYING SHRINKAGE
DIAGONAL CRACKING	
APPEARANCE:	SHALLOW IN DEPTH, ROUGHLY PARALLEL, FORM AT AN ANGLE OTHER THAN 90 DEGREES WITH ROADWAY CENTERLINE
MECHANISMS:	EARLY AND LONG-TERM DRYING SHRINKAGE
	ASSOCIATED WITH SUPERSTRUCTURE SKEWS, ESPECIALLY ACUTE ANGLES
PATTERN CRACKING	
APPEARANCE:	INTERCONNECTED NETWORK RESEMBLING DRIED MUD FLAT
MECHANISMS:	EARLY AND LONG-TERM DRYING SHRINKAGE
RANDOM CRACKING	
APPEARANCE:	IRREGULAR AND NO SPECIFIC FORM
MECHANISMS:	EARLY AND LONG-TERM DRYING SHRINKAGE

an angle other than 90 degrees with the roadway centerline. These cracks are caused by early and long term drying shrinkage and are associated with superstructure skews, especially acute angle corners (6,12).

- Pattern or map cracks, also caused by early and long term drying shrinkage, are characterized by an interconnected network of cracks that resemble those of a dried mud flat (12).

- Random cracks are those that occur irregularly on the slab surface and essentially have no specific form. These cracks are caused by the tensile stresses related to drying shrinkage and live load stresses (6,12).

As previously stated, these other forms of cracking have only a secondary role in the deterioration of concrete bridge decks. A complete description of these cracks is contained in the MIT research report R83-01 on "Concrete Bridge Deck Deterioration and Repair" by Balduman and Buyukozturk.

2.3 SCALING

Scaling is primarily a form of freeze-thaw deterioration, characterized by the flaking of surface mortar and often accompanied by the loosening of surface aggregates (6,12,26). In its severest form, scaling can be a complete breakdown of the mortar portion of the concrete (26). Studies have indicated that the contributing factors to scaling include: excessive or late finishing, variation in air content and slump, inadequate dispersion of entrained air,

poor drainage, and heavy application of deicing salts (6,12,105). Furthermore, the actual deterioration mechanism associated with scaling have been explained by hydraulic pressure, osmotic pressure, capillary ice growth, differential behavior between the surface and lower layers of concrete, and various other hypotheses (Table 2-2).

The prevailing explanation of this deterioration (references 6,12,105) is as follows: An initial period of supercooling occurs when the concrete cools below the freezing point of water. Subsequently, ice crystals form in the large capillaries within the concrete. The water in the cement paste is a weak alkali solution. Thus, during freezing, the alkali content of the unfrozen portion of this solution in these capillaries increases. Water migrates from the unfrozen pores to the frozen cavities due to osmotic pressure. As a result of this dilative pressure due to ice accretion and osmotic pressure in the pores, mechanical damage or cracking in the cement paste occurs. In addition to damage in the cement paste, aggregate particle failure can occasionally occur during freezing. But, unlike cement paste failure, water migrates away from and not toward the sites of ice accretion during aggregate particle failure. As the pores become critically saturated, pressures are developed due to the resistance to this migration of water away from the regions of freezing. Consequently, these pressures result in aggregate particle failure. However, under most exposure

TABLE 2-2

SCALING MECHANISMS AND PARAMETERS

SCALING	
APPEARANCE:	FREEZE-THAW DETERIORATION RESULTING IN FLAKING OF SURFACE MORTAR, OFTEN ACCOMPANIED BY LOOSENING OF SURFACE AGGREGATE
TYPES	**MECHANISM**
CEMENT PASTE FAILURE	DURING FREEZING PERIODS, ICE CRYSTALS FORM IN LARGE CAPILLARIES WITHIN THE CONCRETE ALKALI CONTENT OF THE UNFROZEN PORTION OF WATER SOLUTION IN THE CAPILLARIES INCREASES WATER MIGRATES FROM UNFROZEN PORES TO FROZEN CAVITIES DUE TO OSMOTIC PRESSURE MECHANICAL DAMAGE TO CEMENT PASTE OCCURS FROM THE DILATIVE PRESSURE DUE TO ICE ACCRETION AND OSMOTIC PRESSURE IN PORES
AGGREGATE PARTICLE FAILURE	OCCURS ONLY OCCASIONALLY WATER MIGRATES AWAY FROM SITES OF ICE ACCRETION PRESSURES DEVELOP IN SATURATED PORES DUE TO RESISTANCE OF MIGRATION CAUSING AGGREGATE FAILURE
CONTRIBUTING FACTORS:	EXCESSIVE OR LATE FINISHING VARIATION IN WATER CONTENT & SLUMP POOR DRAINAGE HEAVY APPLICATION DEICING SALTS INADEQUATE DISPERSION OF ENTRAINED AIR
CORRECTIVE ACTION:	AIR ENTRAINMENT APPLICATION OF 50/50 MIX LINSEED OIL AND KEROSINE OR MINERAL SPIRITS

conditions, the aggregate is unlikely to become critically saturated because of the self-desiccation (drying out) that occurs during hydration of the cement and evaporation loss.

Air-entrainment is the proven method of minimizing and avoiding freezing damage in the cement paste (6,105). The large pores do not fill with water except after prolong exposure to 100% relative humidity and empty on the slightest decrease below that level. The entrained air voids are available to act as reservoirs and compete with large capillaries for water migrating from smaller pores. This assists in relieving the hydraulic or osmotic pressure. A study of bridge decks in 8 states indicated non air-entrained concrete decks exhibited higher frequency of scaling, more extensive scaling per unit area, and more severe forms of scaling (6). But, in the presence of deicing salts, air entrainment does not give complete protection against scaling (6,12,105). The salt increases the degree of saturation of the concrete because the low vapor pressure of the salt solution makes it more probable that the entrained air voids will fill with water and not be available to act as a reservior. Upon near saturation, air-entrained concrete is susceptible to frost damage due to its relatively high porosity and the large amounts of freezable water it now contains. Exposed concrete deck slabs are unlikely to become saturated with water. However, saturation is very likely on asphalt covered decks without an intervening membrane. Resistance to frost damage

can also be improved by reducing porosity (hence water-cement ratio) because this reduces the amount of freezable water per unit volume of concrete.

If air-entrained concrete is not used, an alternative protection system is two applications of a 50/50 mixture of boiled linseed oil and either mineral spirits or kerosene (8,26). A recent Federal Highway Administration survey established that 18 states routinely use this technique. In the case of severe scaling, a complete deck survey and a minimal recommendation of an overlay is suggested (26). In some instances, deck replacement may be more cost effective.

2.4 WEAR AND POLISHING

Generally, wear and aggregate polishing have not caused serious concrete bridge deck deterioration. Nevertheless, they play an important factor in the service life of an exposed concrete deck. Differential wear in the wheel paths can cause water to be ponded there, both decreasing highway safety and accelerating concrete deterioration (105). This wear can also lead to aggregate polishing and the associated hazardous condition of reduced skid resistance (26). Remedies for polishing vary with concrete condition and cover depth. For instance, for sound concrete and sufficient cover depth, skid resistance is improved by sawing transverse grooves 1/8 inch in width by 1/8 - 3/16 inches in depth (26). This technique prevents hydroplaning by allowing water to escape beneath the tires. Otherwise, a bituminous concrete overlay,

to include a waterproofing membrane to prevent and limit chloride passage into the deck, is recommended.

2.5 SPALLING

Spalling is the major curse of contemporary concrete bridge decks, being the most destructive deterioration mechanism (6,26,92). Unlike scaling, essentially a surface phenomenon, spalling is the removal of concrete fragments from the deck surface, possibly exposing the reinforcement steel and causing the removal of entire pieces of concrete through the depth of the section (6). Moreover, spalling is directly related to the use of deicing chemicals and results primarily from the corrosion of the reinforcing steel. Other secondary spalling mechanisms include fracture plane formation and tire pumping (Table 2-3).

2.5.1 CORROSION-INDUCED SPALLING

Uncracked, uncontaminated concrete normally has ample resistance to corrosion attack due to its high pH value. However, corrosion-induced spalling begins when chloride ions in a soluble form penetrate the concrete to the level of the reinforcing steel from either slow permeation, transverse cracks, or bleed water channels (6,12). Once the chloride ion concentration exceeds a threshold value, the passivity of the steel (its ability to form a protective, hydrogen film) is destroyed (26). Hence, corrosion of the reinforcement steel begins in the presence of chloride, oxygen and

TABLE 2-3

SPALLING MECHANISMS AND PARAMETERS

SPALLING

APPEARANCE: REMOVAL OF CONCRETE FRAGMENTS FROM DECK, POSSIBLE EXPOSURE OF REINFORCEMENT AND REMOVAL OF ENTIRE PIECES THROUGH SECTION DEPTH

TYPE	MECHANISM
CORROSION-INDUCED	CHLORIDE IONS PENETRATE TO STEEL LEVEL
	CORROSION FORMS IN PRESENCE OF CHLORIDE, OXYGEN, AND MOISTURE
	INTERNAL TENSION FORCES FROM CORROSION CAUSES SPALLS
FRACTURE PLANE	REINFORCEMENT OFFERS RESISTANCE TO CONCRETE SETTLEMENT, CREATING PLANE OF WEAKNESS AND VERTICAL CRACKS
	WATER OR CHLORIDE SOLUTIONS PENETRATE CRACKS AND FILL VOIDS ADJACENT TO REINFORCEMENT
	FREEZING ACTION CREATES PRESSURE AND FRACTURE PLANE
TIRE PUMPING	HEAVY TRAFFIC CREATE WHEEL PATHS THAT COLLECT SALT AND MOISTURE
	TIRE PRESSURE CREATES PUMPING ACTION FORCING CHLORIDE IONS INTO CONCRETE DECK

CONTRIBUTING FACTORS:
- INADEQUATE COVER & POOR DRAINAGE
- HIGH CHLORIDE CONCENTRATIONS
- INSUFFICIENT CONSOLIDATION
- HIGH WATER-CEMENT RATIO

CORRECTIVE ACTION:
- ADEQUATE COVER 2-3 INCHES
- LOW WATER-CEMENT RATIO $\leq .40$
- PROPER CURING AND CONSOLIDATION
- ADEQUATE DRAINAGE

moisture. As the corrosion products accumulate on the reinforcing steel surface, internal tension forces are exerted on the surrounding concrete, and spalls are formed (Figure 2-2). These spalls have two distinctive shapes. The typical shape, caused by point sources of internal pressures, is characterized by a V-shape with the apex at the reinforcing steel (6). Another shape consists of a vertical crack over the reinforcement steel, horizontal cleavage away from the steel, and fragmented concrete at distant points from the reinforcement. Often times, these cracks initiated at the corroded bar may spread horizontally until reaching other similar crack (Figure 2-3). This action results in delaminations, which are characterized by a separation of the concrete layers parallel to the deck surface (6,12,105). The repeated action of vehicular loading and the formation of the ice in these delaminated areas then produce the familiar pothole. A very complete description of the corrosion process is provided in the MIT research report R83-01 on "Concrete Bridge Deck Deterioration and Repair" by Balduman and Buyukozturk.

2.5.2 SPALLING ASSOCIATED WITH FRACTURE PLANE FORMATION

Another spalling mechanism, whose effects are secondary to corrosion-induced spalling, is fracture plane formation (6). This mechanism involves the formation of a fracture plane due to a plane of weakness inherent to the deck. The settlement of concrete between reinforcing bars may cause the concrete to bend over the reinforcement and to form vertical

FIGURE 2-2

SPALLING

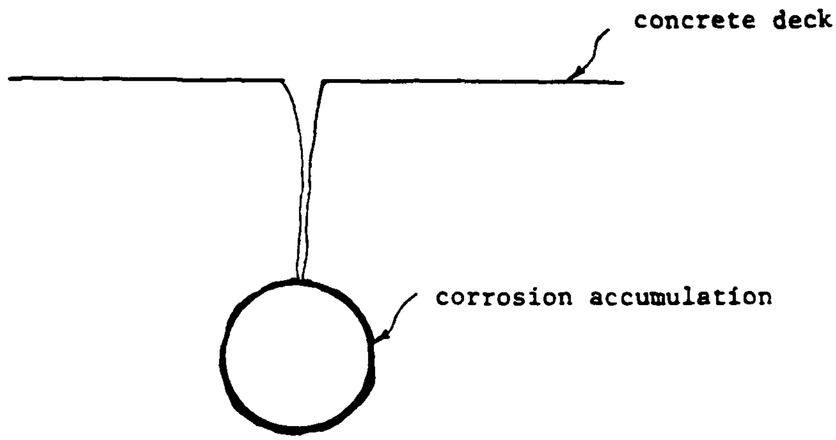
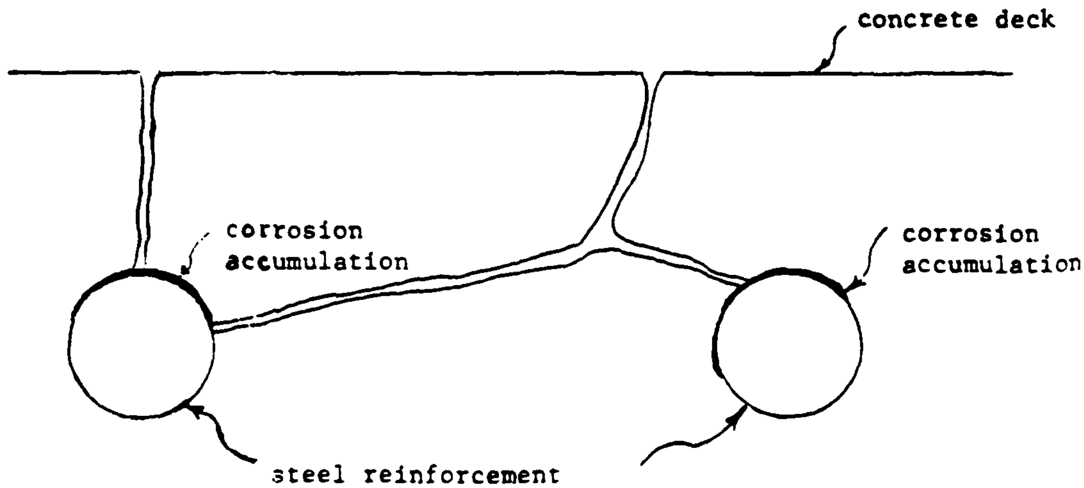


FIGURE 2-3

DELAMINATION



cracks. However, steel reinforcement offers resistance to this settlement, creating a plane of weakness at the level of the top mat of reinforcement. Eventually, horizontal separations between the reinforcing bars and voids along the side of the steel can develop. Water or soluble chlorides penetrate the vertical cracks, filling voids near the reinforcing steel and the weak horizontal plane. Upon freezing of the solution in the voids, pressure in the horizontal plane results in a fracture plane.

2.5.3 SPALLING RESULTING FROM TIRE PUMPING ACTION

Heavy traffic volumes produce wheel paths which are collection points for snow, slush, and salt water solutions. Tire pressure is then transmitted both vertically and horizontally through the water film to the exposed concrete deck, creating downward pressure behind the tire. As a result of a developing pump action, chloride ions are forced into these areas at a faster rate than other areas (6,12). Hence, corrosion and spalling often occur initially in the wheel areas.

2.5.4 PARAMETERS AFFECTING SPALLING

Corrosion of the reinforcement steel and subsequent spalling is more likely to occur when high concrete permeability, high chloride concentrations, inadequate cover, high water-cement ratio, and insufficient consolidation exists (6,12,19). For instance, a Pennsylvania study revealed 53 of

55 severely spalled decks had concrete covers less than the specified design value (6). Both the chloride penetration and chloride content within the concrete deck decrease with depth. Thus, a thicker cover provides greater corrosion protection (10,73,92). Moreover, studies indicate that spalls occur only in areas where vertical cracks appear directly over the top reinforcing steel (92). For concrete covers less than 2 inches, the cracks are predominantly over the top reinforcing steel and spalls appear (92). For covers greater than 2 inches, the cracks are normally random or pattern in nature and spalls seldom occur (92). As previously inferred, a low water-cement ratio is capable of decreasing the concrete permeability and the resulting chloride content. FHWA experimental studies have disclosed that concrete with a water-cement ratio of 0.40 is more corrosive resistant than concrete with a water-cement ratio of 0.50 or 0.60 (6,19). Furthermore, studies by the Kansas DOT have estimated that increasing the cover from 2 inches to 3 inches and also decreasing the water-cement ratio of the concrete from 0.44 to 0.35 can triple the life of a deck (105). Insufficient consolidation, another parameter affecting spalling, increases concrete permeability and the corrosion potential of the concrete bridge deck (19). Additionally, corrosion is obviously linked to high chloride concentrations. Regarding this specific parameter, the chloride content corrosion threshold represents the minimum amount of chloride necessary to initiate corrosion, in the presence of oxygen and moisture,

of the reinforcing steel. Although difficult for universal application, the FHWA has estimated this threshold value to be approximately 2.0 lbs of calcium chloride per cubic yard of cement (26). Certainly, an understanding of these various parameters can ultimately influence bridge deck design and construction practices.

2.6 SUMMARY AND CONCLUSIONS

Bridge deck deterioration primarily undertakes the following forms: cracking, scaling and spalling. Transverse cracking, caused by concrete shrinkage, is the most predominant and important type of cracking. This cracking has been associated with specific superstructure types and increasing span lengths. Scaling, the second form of deterioration, is caused by the action of repeated freeze-thaw cycles in concrete. Hypotheses for this phenomenom have primarily focused on hydraulic pressure, osmotic pressure, and capillary ice growth. Adverse curing procedures, extensive use of deicing salts, and poor drainage systems affect the resistance of concrete decks to this form of deterioration. Moreover, the use of air-entrained concrete has a significant effect in preventing scaling. Spalling, the most critical form of deterioration, results from internal tensile forces within the concrete due to corrosion accumulation. Other secondary mechanisms for spalling include fracture plane formation and tire pumping. Furthermore, inadequate cover, high concrete permeability, a high water-cement ratio, poor drainage, high

chloride content from deicing salts, and insufficient consolidation are the significant parameters associated with this critical form of deterioration.

There are several meaningful conclusions that can be inferred from this discussion of concrete deterioration mechanisms:

- first, the importance of specifying and enforcing strict design standards for both new deck construction and rehabilition efforts, to include: adequate concrete cover, a low water-cement ratio, usage of air-entrained concrete, proper drainage, the use of membranes or other protective systems, and proper curing procedures. Many of the bridges in the Northeast were either constructed without understanding these corrosion related design features or constructed without effective inspections to insure proper specifications were being adhered to. An example of such design standards would be the American Concrete Institute (ACI) current recommendations of a minimum of 2 inches of cover for bridge decks with a water-cement ratio of 0.40 and 2 1/2 inches for a water-cement ratio of 0.45 (19,105).

- the need to examine the current deicing policy and procedures within a state in order to minimize the level of use and still maintain adequate serviceability or safety constraints. Salting as a matter of "insurance" rather than as a result of "need" should be avoided (95). The possible use of alternatives to deicing salt must be an area of

continued research.

- the need to document fully both the initial construction specifications and maintenance or rehabilitation history associated with bridge decks. As an example, 75 percent of all states reported in 1979 that only 10 percent of their bridges had some sort of protective system (e.g., a waterproof membrane). Knowledge of the existence of a protective system may impact upon several bridge management issues, such as the selection of bridges for inspection, the methods of inspection, and decisions concerning the likelihood of deterioration over time, preventive maintenance efforts, and rehabilitation or replacement techniques.

- the appearance of a highly deteriorated concrete matrix in bridge decks that have high chloride contents but no apparent corrosion of the reinforcing steel (a phenomenom mentioned consistently by the member states of the New England Surface Transportation Infrastructure Consortium) may result from extensive freeze-thaw scaling (caused by saturation in those asphalt-covered decks without an intervening membrane) or spalling due to secondary fracture plane causes (6,34). Additional research into the true nature and causes of this form of deterioration is necessary.

- the need for adequate preventive maintenance, such as insuring proper drainage and eliminating water accumulation areas on the deck.

- and, the need to thoroughly understand the conditions under which reinforcing steel in concrete will corrode.

Specifically, several New England states have indicated that the chloride content corrosion threshold value may be larger than the FHWA recommendation (99-103). These states have found incidents where high chloride concentrations exist with no apparent corrosion of the reinforcing steel. This may be explained by the lack of sufficient oxygen but, more likely, by the lack of moisture to trigger the corrosion process. Thus, both the chloride content corrosion threshold value and the minimum moisture content necessary for corrosion must be ascertained.

CHAPTER THREE

BRIDGE DECK EVALUATION

3.1 INTRODUCTION

As previously stated, the purpose of this thesis has been to focus on the decision-making process involving the dilemma of repair versus replacement strategies for deteriorated bridge decks. The previous chapter identified the deterioration mechanisms that are the source of this dilemma. But merely to understand the mechanisms is not sufficient. Normally, the condition and performance of decks are so highly variable that an individually engineered solution is required for each structure. Thus, a reliable condition survey or assessment of an overall bridge structure and, specifically, the bridge deck is a critical element in the systematic and cost-effective approach of formulating repair/replacement strategies. Essentially, a condition survey is required for either of two reasons:

- to establish repair/replacement priorities on a statewide scale, or
- to provide details of the nature and extent of concrete deterioration needed for the design and execution of the restoration work (70).

Moreover, these condition surveys fall into two categories: a general survey and a detailed, preconstruction survey. This condition survey information, once collected and stored in a data-base, provides not only the structural condition

assessment of the deck, superstructure and substructure, but also indicates safety, serviceability, functional adequacy, and the estimated remaining life of the bridge and its deck component. This information provides essential input in the development of a needs analysis, the initial step associated with the often complex repair or replacement decision-making process, which will be addressed in detail in Chapter Six.

This chapter will be divided into four basic sections. The first section will discuss the general characteristics and scope of the two categories of condition survey. The second section will focus on the shared concerns regarding the current survey techniques expressed by the New England Surface Transportation Infrastructure Consortium. In fact, the magnitude of these concerns was the impetus for the consortium formation. The role of condition surveys in the decision-making process will be the focal point of the third section. Finally, several conclusion will be inferred from the previous sections. A thorough description of the current test methods associated with a detailed survey, the number of samples required, and the sequence of operations are presented in the research by Westover and the Transportation Research Board (105,116).

3.2 GENERAL SURVEY

The Surface Transportation Assistance Act of 1972 man-

dated all public bridges be inspected and inventoried in accordance with the National Bridge Inspection Standards (81). Thus, the general or routine survey occurs on a regular basis, often at the two-year interval associated with the National Bridge Inventory data collection. However, regardless of the mandatory Federal Act, a periodic bridge inspection is necessary for both old and new bridges. Older bridges were often designed for small load capacities and low traffic volume. Additionally, as a result of the age and service environment, the materials may have deteriorated. Although new bridges may have been designed according to current traffic and load constraints, an inspection may indicate design flaws or poor workmanship in construction. Thus, the primary purpose of these routine or general condition surveys is not only data acquisition and record keeping for the National Bridge Inventory, but also public assurances of safety (53, 81). During these surveys, structural and functional adequacy, initial priorities for maintenance, repair and replacement projects, and the need for more detailed inspection are being analyzed (64). This general survey provides an overall rating of component elements of the bridge, to include the substructure, superstructure and the deck, so that future restoration, where needed, can be programmed (Table 3-1). For exposed concrete deck slabs, the general survey is primarily a visual inspection that measures the extent of cracking, scaling and spalling as a percentage of the overall deck area. The visual inspection normally is

TABLE 3-1

CONCRETE BRIDGE DECK CONDITION RATINGS (28)

Category Classification	Rating	Condition Indicators (% deck area)			
		Spalls	Delaminations	Electrical Potentials	Chloride Content #/CY
Category # 3 Light Deterioration	9	none	none	0	0
	8	none	none	none >0.35	none >1.0
	7	none	<2%	45% < 0.35	none >2.0
Category # 2 Moderate Deterioration	6	< 2% spalls or sum of all deteriorated and/or contaminated deck concrete < 20%			
	5	< 5% spalls or sum of all deteriorated and/or contaminated deck concrete 20 to 40%			
Category # 1 Extensive Deterioration	4	> 5% spalls or sum of all deteriorated and/or contaminated deck concrete 40 to 60%			
	3	> 5% spalls or sum of all deteriorated and/or contaminated deck concrete > 60%			
Structurally Inadequate deck	2	Deck structural capacity grossly inadequate			
	1	Deck has failed completely Repairable by replacement only			
	0	Holes in deck - danger of other sections of deck falling			

supplemented by other measurements, such as concrete cover depth, half-cell potential of the reinforcing steel, chloride content, and detection of delaminated areas (70). However, the visual inspection of asphalt-covered decks, which represents the vast majority of the New England States' bridges, is extremely difficult since the asphalt masks the concrete deck surface conditions (98-105). Nevertheless, indicators of deteriorating concrete beneath the asphalt are cracking, especially radial cracks, and wet spots in the asphalt (105). Moreover, greater emphasis must be placed on the underside condition of the deck where cracks, leakage, wet spots and efflorescence are signs of concrete deterioration (105). Normally, for asphalt-covered bridge decks, other evaluation techniques must be employed, especially if the underside of the bridge is inaccessible. Therefore, in most cases, it will be necessary to take core samples, conduct half-cell readings or chloride content measurements, and remove small sections of the asphalt cover to determine the condition of the concrete (70).

3.3 DETAILED, PRECONSTRUCTION SURVEY

The detailed preconstruction surveys are characterized as expensive and conducted on bridge decks programmed for unspecified repair/replacement work. The purpose is to provide enough information to select the appropriate technique for correcting bridge deck deterioration and to prepare the corresponding contract documents (70). For those bridge

decks where replacement is obvious, detailed testing is often unnecessary. However, for those bridge decks in the so-called grey zone (condition code 4-6), these detailed surveys assist in assessing the bridge deck condition, selecting the appropriate repair or replacement strategy, and avoiding unexpected contractor work, excessive costs and difficult contract administration. The factors that affect the nature of the detailed condition survey include (105):

- the type of structure,
- the nature and degree of deterioration,
- the location and traffic density,
- the priority and schedule of the repair or replacement,
- the policy for timing and type of available repair/replacement alternatives, and
- the available human and financial resources.

Thus, the data from detailed condition surveys are a critical element in the decision-making process.

There are currently a variety of different inspection techniques associated with the detailed, preconstruction investigations. The detailed, preconstruction inspection involves not only visual inspection techniques but also techniques that measure cover depth, delamination detection, chloride content, and corrosion potential. As was true for the general survey, asphalt-covered decks are more difficult to evaluate than decks with an exposed concrete surface. Consequently, the cost of the detailed survey for an asphalt-

covered deck will be greater and the reliability of the data lower. For the majority of cases, the detailed survey will include the following items (70):

- For decks with a bituminous overlay, the condition and thickness are determined and significant cracks in the wearing surface are recorded.

- For decks with a waterproofing membrane, the membrane condition is appraised and and the membrane is identified by type.

- Delaminated concrete, scaled areas, patched and open spalled areas, and significant cracks on exposed concrete deck surfaces are recorded and measured.

- Concrete cover to the top mat of reinforcing steel is measured. On asphalt-covered decks, sections of the asphalt overlay must be removed prior to taking this measurement.

- By measuring half-cell potentials, the corrosion activity of the top layer of reinforcing steel is determined. For asphalt-covered decks, holes are drilled through the bituminous overlay to the deck surface to ensure a good electrical contact.

- The general condition of the concrete slab is assessed by removing sections of the asphalt overlay and by coring.

- Concrete core samples are analyzed to determine chloride content, air void system, and compressive strength.

- Inspection of the underside of the deck slab for deteriorated concrete, wet areas, efflorescence, significant cracks, corrosion spalling, and other defects is undertaken.

- Inspection of deck drains occur in order to determine condition, position, and adequacy.

- Sidewalks, handrail posts, curbs, and other components of the bridge above the riding surface are inspected.

- Condition, type, and measurement of expansion and fixed joints and expansion assemblies are determined and special features needed for future reconstruction are identified.

- Other parts of the bridge structure that should be repaired or replaced as part of a rehabilitation/replacement contract for the deck are identified.

The end result of this detailed condition survey is a comphrensive report that documents the condition of the deck slab and its components. Included in the report should be plans, core logs, photographs, tables and test data. As previously mentioned, the specific description of various inspection techniques (Table 3-2) is contained in the research by Westover and the Transportation Research Board (105,116).

3.4 CONSORTIUM EVALUATION OF CURRENT INSPECTION PRACTICES

Meetings with the various transportation agencies of the New England states have clearly identified several consensus views concerning the current bridge deck inspection techniques (98-103). First, all states agreed that reliable and accurate deck assessments of deterioration are necessary for establishing project priorities and identifying the extent of repair and replacement work required. Previously, when a

TABLE 3-2

INSPECTION TECHNIQUES FOR CONCRETE BRIDGE DECK

INSPECTION METHOD	DETECTION CAPABILITY
VISUAL INSPECTION	CRACKS, SPALLING, SCALING, RUST
PACHOMETER (CONCRETE COVER MEASUREMENT)	POSSIBLE CORROSION ACTIVITY
MANUAL SOUNDING INSPECTION (CHAIN DRAG & HAMMER)	DELAMINATIONS
ACOUSTIC DEVICE (DELAMTEC)	DELAMINATIONS
CHLORIDE CONTENT MEASUREMENTS	CORROSION ACTIVITY
ELECTRICAL POTENTIAL MEASUREMENTS (HALF-CELL)	CORROSION ACTIVITY
ELECTRICAL RESISTANCE TESTING	POSSIBLE CORROSION ACTIVITY (EFFECTIVENESS OF MEMBRANES TO CHLORIDE INTRUSION)
INFRARED THERMOGRAPHY	DELAMINATIONS
GROUND-PENETRATING RADAR	CORROSION AND DELAMINATIONS

large number of extremely deteriorated decks existed, the importance of prioritizing projects was relatively minimal. However, the quantity of extremely deteriorated decks has diminished. Consequently, establishing priorities has now become critical in order to focus limited funds in the most cost-effective manner. Thus, reliable and accurate assessment must occur.

A second view is that the current techniques for inspection are adequate for <u>exposed</u> concrete bridge decks where lane closure is feasible. However, for the vast majority of bridges, asphalt-covered and often heavily traveled, the current techniques for assessing the deck condition are inadeqate. An examination of the techniques currently used by the New England states (Table 3-3) indicates that these methcds are labor intensive and time consuming. Also, the states have further indicated that lane closure is often required and reliability on asphalt-covered decks is insufficient. For example, the chain drag technique can not differentiate between debonding and delaminations on asphalt-covered bridges. Therefore, application can only occur once the asphalt has been stripped away. The most commonly used deck protection system in the New England states is the waterproof membrane. Yet, the unreliability and difficulty associated with the electrical resistivity technique, a technique used to measure membrane permeability, has precluded its use. Visual inspection of asphalt decks is problematic in that

TABLE 3-3

SUMMARY OF INSPECTION TECHNIQUES USED BY

NEW ENGLAND SURFACE TRANSPORTATION CONSORTIUM (98-103)

TECHNIQUE	ME	NH	VT	RI	MA
VISUAL	X	X	X	X	X
CHLORIDE ION CONTENT	X	X	X	X	X
CORINGS	X	X	X	X	X
HALF-CELL POTENTIAL		X	X	X	
CHAIN DRAG	X	X	X	X	X
ELECTRICAL RESISTIVITY		X			

NOTE: VERMONT PLACES LITTLE EMPHASIS ON CHLORIDE ION TESTING

MASSACHUSETTS PRIMARILY EMPHASIZES CHLORIDE ION CONTENT TESTS ONLY FOR BRIDGE DECKS WHERE FEDERAL FUNDING IS DESIRED.

there may be no correlation of the condition of the asphalt and the condition of the underlying concrete deck. Thus, there is a need for affordable, new technology to improve the reliability, the speed of collection, and coverage of condition assessment data. Such technology must have the capacity to identify incipient deterioration conditions and thus promote effective preventive maintenance.

Often times, the results of one test will not correlate well with another. This frequently occurs when comparing the extent of corrosion for the half-cell potential test and the chloride ion content test. As a result, there is a disperity in the use of certain inspection techniques. Vermont relies heavily on the use of the half-cell potential test while Maine has abandoned this test and relies on the chloride ion content technique. Thus, there must be improved and more objective interpretation procedures developed for both current and newly developed inspection techniques.

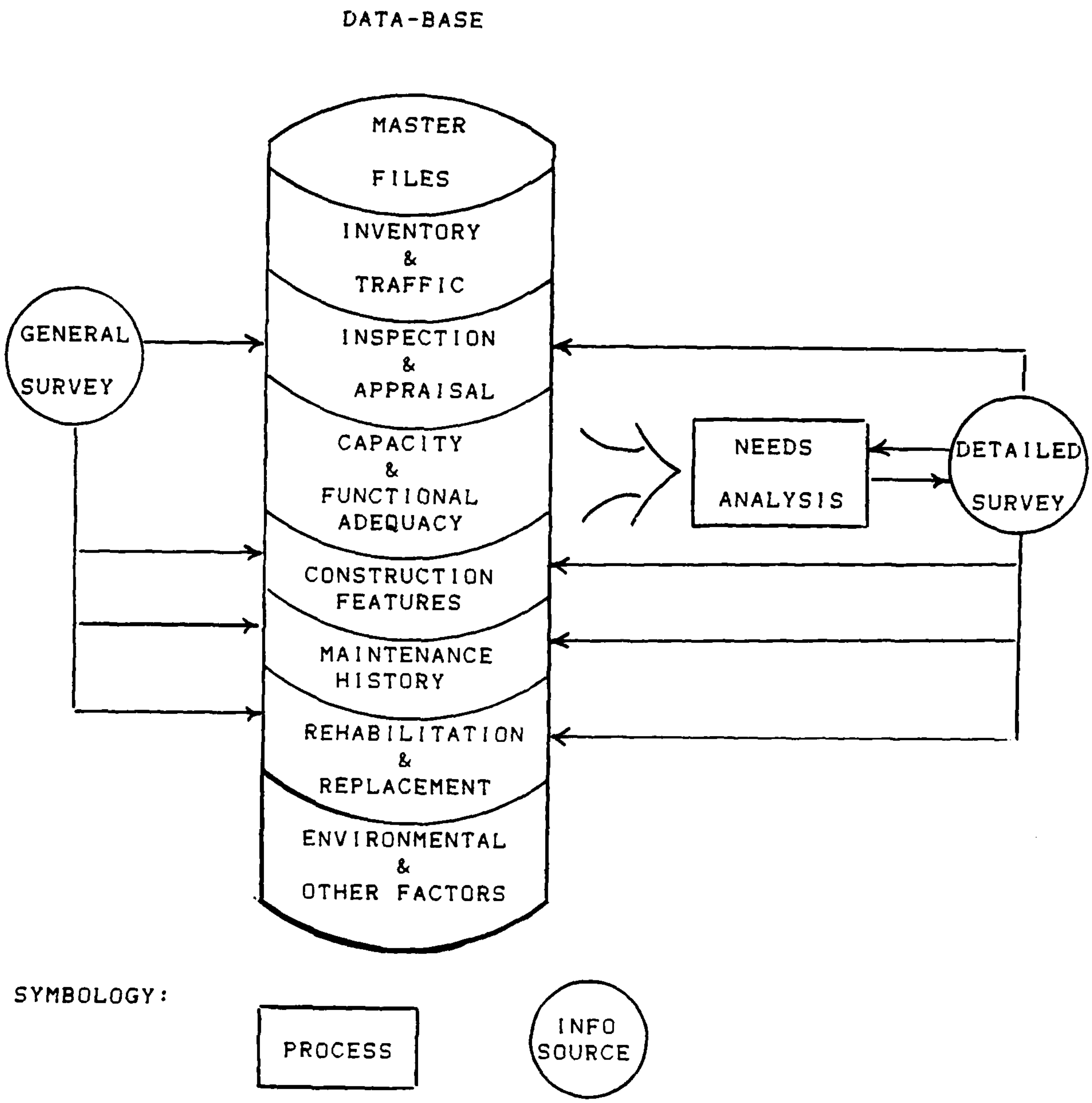
3.5 APPLICATION TO THE DECISION-MAKING PROCESS

The subsequent application of both the general and the detailed, preconstruction condition surveys is illustrated in Figure 3-1. As illustrated, the general condition survey provides critical input into the Bridge Inspection and Appraisal data-base file. This stored data reveals unsafe conditions, serviceability considerations, the overall sufficiency rating of the bridge, and condition assessment of bridge components (to include the deck). Additionally, data

FIGURE 3-1

ROLE OF DECK EVALUATION

IN THE DECISION-MAKING PROCESS



that relates to the adequacy of construction features (such as concrete cover thickness), previously performed maintenance operations, and the performance characteristics of prior rehabilitation or replacement alternatives, is provided by the general survey. This data, in conjunction with other data-base files, is used to develop a needs analysis, which will be explained in greater detail in Chapter Six. This need analysis is essentially an initial prioritized listing of bridge decks that must be considered and investigated for rehabilitation or replacement.

A detailed, preconstruction survey is subsequently performed to more accurately quantify the degree of deck deterioration in order to select the appropriate restoration alternative. Consequently, the results of a detailed survey may also verify or modify the priority of the projects in the needs analysis. For instance, the detailed survey of a particular deck project may indicate that the deck condition is much worse than previously determined in the general survey. Accordingly, this project may eventually have a higher priority. As Figure 3-1 further illustrates, the results of this detailed, preconstruction survey are additional data elements to be channeled back into the Structure Inspection and Appraisal data-base file. Additionally, this data is analyzed with respect to the performance characteristics and service life of previously performed rehabilitation and replacement techniques. For instance, if the

bridge deck currently has a waterproof membrane, this detailed condition survey of the bridge deck can provide additional input that may clarify the performance of the membrane in resisting chloride intrusion or the service life associated with a particular membrane application. Thus, over a number of years, this information from bridge inspection results can be used to improve the quality of the data contained in the Rehabilitation and Replacement data-base file.

3.6 SUMMARY AND CONCLUSIONS

The keystone to formulating repair/replacement strategies for deteriorated bridge decks is the condition assessment of these decks. This data defines the extent of deterioration, assists in the selection of the appropriate restoration technique, and contributes to project prioritization. The general, or routine, survey which occurs on a regular basis provides the overall component ratings that assist in identifying potential projects. The subsequent detailed, preconstruction survey validates and enhances the deck assessment and thus provides the illuminating information that clarifies the repair/replacement dilemma.

There are several significant conclusions that can be inferred from this discussion of bridge deck evaluation contained in this chapter:

- The evaluation techniques, each of which have a specific purpose and certain limitations, are components of an overall evaluation system and not competitive options.

Thus, no one method should be used to make an evaluation since the interrelationship of results of different tests have been confirmed a number of time (105).

- The use of the test methods as part of an overall condition survey enables identification of anomalous readings associated with one test method and thus clarifies condition assessment. For instance, although corrosion is linked to inadequate cover, corrosion can occur with adequate cover where the deck concrete is of a poor quality (6). Therefore, relying solely on a pachometer technique would be inappropriate.

- Evaluating the condition of asphalt-covered decks is much more difficult than for exposed concrete decks. Delamination and pachometer surveys are generally unsatisfactory; visual examination of the deck underside must be greatly emphasized; more corings and dry sawings may be required.

- There is a need to examine the current assessment techniques and develop improved and more objective interpretation techniques.

- There is a need for a nondestructive method of measuring the rate of corrosion. Although existing half-cell and chloride content techniques can indicate corrosion, the rate of the reaction is unknown. The effectiveness of a deck protection system is related to this corrosion rate.

- There is a need for some test to measure the oxygen concentration in concrete. Although there may a chloride concentration level that exceeds the generally recognized

chloride threshold, corrosion can only occur if there is adequate water and oxygen concentrations.

- There is a need for further analysis and development of insitu techniques, such as infrared thermography and ground-penetrating radar. Such techniques offer the possibility of rapid evaluation of the bridge deck condition, minimization of lane closure and the associated cost, and evaluation of asphalt-covered decks without extensive coring or partial removal of the asphalt by sawing. These techniques may also be able to identify the incipient or the earliest stages of deterioration. Too often, the deterioration is ascertained only when it has reached an excessive level, warranting a costly rehabilitation or replacement solution.

- It is critical that the results of condition surveys be analyzed and incorporated into a number of data-base files. Bridge evaluation techniques can offer valuable information related to construction design standards, the choice of new construction methods, the performance characteristics or effectiveness of various protection systems or repair alternatives, the service life associated with construction or rehabilitation techniques, the estimated remaining life of the bridge and its deck, the estimated time to next maintenance or rehabilitation effort, and many other data-base items. Deck evaluation results can not be confined soley to a "structural inspection and appraisal" file.

The next chapter will illustrate how the National Bridge

Inventory data, which includes deck assessment data, contributes to the bridge deck repair versus replacement decision-making process.

CHAPTER FOUR

NATIONAL BRIDGE INVENTORY AND INSPECTION PROGRAM

4.1 INTRODUCTION

The purpose of this chapter is to emphasize the importance of the National Bridge Inventory (NBI) data as part of the overall data-base used in the deck repair/replacement decision-making process. In the development of this chapter, the historical origin of the NBI and Inspection Program, the purpose of the program, and the initial trends and observations associated with the NBI data are discussed. Additionally, the federal funding program that is inherently linked to the NBI, the validity of the NBI data, and the application of this data to the decision-making process are salient topics. The selection of the appropriate repair/replacement strategies for deteriorated concrete bridge decks is highly dependent upon a detailed condition assessment and an analysis of both the available National Bridge Inventory (NBI) data and other pertinent bridge-related information that is collected by the States. The National Bridge Inventory data essentially consists of bridge structure inventory and traffic data, bridge inspection and appraisal data, and structural capacity and functional adequacy data. Based upon this data, sufficiency ratings can be developed for each bridge structure. Furthermore, bridge decks that require restoration work can be identified and appropriate rehabilitation/replacement strategies can be formulated. Nevertheless, the

NBI data, plagued by invalid or illogical entries, is not being used to its fullest potential by any state, to include the New England states. Additionally, each state should seriously consider adding several data elements, which are necessary for analyzing repair versus replacement options, to their NBI data-base.

4.2 HISTORICAL ORIGIN OF THE NBI AND INSPECTION PROGRAM

The National Bridge Inventory and Inspection Program is less than two decades old. The impetus for this program was the tragic December 1967 collapse of the Silver Creek Bridge over the Ohio River (1). The loss of 46 people prompted public outcry and subsequent Congressional hearings, which resulted in the 1970 Federal-aid Highway Act (116). This important act directed the Transportation Secretary "in consultation with the State highway departments" to inventory all bridges on Federal-aid highway system over waterways and other topographical barriers, classify them according to serviceability, safety and essentiality for public use, and finally assign each a priority for replacement (1). Prior to this requirement, many states were unaware of the number of bridges under their authority and lacked a formalized bridge inspection and record keeping procedure to insure bridge safety (90). In April 1972, the National Bridge Inspection Standards (NBIS) was established to provide guidelines for this inspection and inventory requirement (116).

By the end of 1973, most states had inventoried all bridges on the Federal-aid highway system (1). Eventually, the Surface Transportation Assistance Act of 1978 directed the inventory and inspection program to be expanded, to include all highway bridges over 20 feet in length on public roads and controlled by state, county, parish or city governments (29,30). This inventory was to be completed by December 31, 1980. As as result, NBI data on all of the 260,000 bridges on the Federal-aid highway system and 98% of the 314,000 bridges on all other public roads has been collected (1). The current National Bridge Inventory data (Figure 4-1), to include the recent historic bridge item, consists of 89 attributes per bridge record: 58 involving inventory items, 15 condition and condition appraisal items, and 16 items describing proposed renovations (1,12,28). Under the current NBIS guidelines, "each bridge must be inspected at regular intervals not to exceed two years" in accordance with the AASHTO "Manual for Maintenance Inspection of Bridges 1978" (1,29,30).

The depth and frequency of inspection will depend highly on such factors as: age of the bridge system, traffic characteristics, state of maintenance, known deficiencies, availability of inspection personnel, special equipment and expert personnel, size and complexity of the bridge, previous inspection results, and preferences of the inspection organization (1,29,30). Moreover, all inventories, inspections, and appraisals are done at the direction of state and local

FIGURE 4-1

FHWA STRUCTURAL INVENTORY AND APPRAISAL SHEET (28)

STRUCTURE INVENTORY & APPRAISAL SHEET

Revised 12-78

IDENTIFICATION

1 State
2 Hwy District
3 County 4 City/Town
5 Inventory Route On Under
6 Features Intersected
7 Facility Carried by Structure
8 Structure No / of
9 Location
10 Min. Vert. Clearance, Inv. Rte. ' "
11 Milepoint
12 Road Section No
13 Defense Bridge Description
14 Defense Milepoint
15 Defense Section Length
16 Latitude
17 Longitude
18 Physical Vulnerability
19 By pass, Detour Length
20 Toll
21 Custodian
22 Owner
23 F A P No

CLASSIFICATION

26 Highway System
Administrative
Functional

	By	Date
Transfer of Data		
Maintenance Insp		
Condition Analysis		
Appraisal		
Cost Estimate		
General Review		

STRUCTURE DATA

27 Year Built
28 Lanes on Str under
29 ADT 30 Year
31 Design Load
32 Appr Rdwy Width w/Shld
33 Br Median None Open Closed
34 Skew
35 Structure Flared Yes No
36 Traffic Safety Features
37
38 Navigation Control Yes No
39 -Vertical ft
40 -Horizontal ft
41 Open, Posted, or Closed

Type Service code
Structure Type-Main
- Approach
No of Spans-Main
-Approach
Total Horiz. Clearance ft
Max Span Length ft
Structure Length ft
Sidewalk Lt. ft, Rt. ft
Br Roadway Width (curb-curb) ft
Deck Width (out-out) ft
Vert Clearance over Deck ' "
Underclearance-Vertical ' "
-Lateral-Right ft
-Left ft
Wearing Surface

CONDITION

	Material	Condition Analysis	Rating (9-0)
Deck			
Superstructure			
Substructure			
Channel & Channel Protection			
Culvert & Retaining walls			
Estimated Remaining Life	Approach Roadway Alignment		
Operating Rating	Inventory Rating		

APPRAISAL

	Deficiencies	Rating (9-0)
Structural Condition		
Deck Geometry		
Underclearances-Vertical & Lateral		
Safe Load Capacity		
Waterway Adequacy		
Approach Roadway Alignment		

PROPOSED IMPROVEMENTS

Year Needed Completed Describe (item 75)
Type of Service
Type of Work
Improvement Length ft
Design Loading
Roadway Width ft
Number of Lanes Prop Rdwy Improvement-Year
ADT Year -Type

Remarks:

Cost of Improvements $ 000
Prel Engrg $ 000
Demolition $ 000
Substructure $ 000
Superstructure $ 000
Insp Date

governments. In addition to the required biannual inspection, interim inspections are required for bridges that are in questionable condition, have known deficiences, and are posted with a weight limit less than the local legal limit (1). Each state is then required to submit an update of inventory data annually for inclusion into the NBI data-base maintained by the Federal Highways Administration (1,90).

4.3 PURPOSE OF THE PROGRAM

Obviously, the primary purpose of the National Bridge Inventory and Inspection Program is to insure the structural safety of bridges for public use (1). Accordingly, all bridges must be evaluated for safe load capacity (29). Specifically, if the bridge is unsafe to carry a three-ton load, the bridge must be closed (1). Additionally, those bridges that can not carry the maximum state legal load must be posted (29). As of December 1984, nearly 4,500 bridges were closed to all traffic and 148,000 of the nation's bridges required load restrictions (29).

Although the primary purpose of the National Bridge Inventory and Inspection Program is to ensure that each bridge is structurally safe and suited for its designated use, the collection of this data can serve many other functions (1,53,90,116):

- identify actual and potential trouble spots as early as possible.

- record systematically and periodically the state of the bridge structure and thus document bridge needs.

- establish physical records for each bridge.

- infer predictions for the rate of deterioration.

- provide feedback for designers, contractors and bridge owners on features most likely to cause maintenance problems.

- establish cost-effective evaluations of past bridge repair and rehabilitation efforts; provide information for decision-makers concerning maintenance, rehabilitation, or bridge replacement in order to minimize both the direct costs and the consequential costs of traffic restrictions or diversions.

- monitor the effects of changes in the bridge load rating, estimate potential costs to increase load capacity, and establish truck overloading routing.

- plan national defense uses.

- enhance both inspection and maintenance scheduling and group the deficiencies on a number of bridges together in order to deploy resources efficiently and reduce costs.

- promote establishment and documentation of historical bridges.

- serve as a tool for prioritizing bridge replacement and rehabilitation by using a sufficiency index for each deficient bridge.

Thus, the potential use of the National Bridge Inventory data is extensive. Unfortunately, no state has yet taken full advantage of this data (1).

4.4 INITIAL TRENDS AND OBSERVATIONS

The collection of the National Bridge Inventory data has had a tremendous impact in identifying the severity of bridge deterioration within the United States. As a result of this inventory, 41 percent of the nation's bridges, or approximately 236,000 bridges, were identified as structurally deficient or functionally obsolete (29). This structurally deficient category implies that these bridges are restricted to light vehicles only, are closed, or need immediate rehabilitation to stay open. A functionally obsolete category implies that the deck geometry, load carrying capacity (comparison of the original design load to the current state legal load), clearance, or approach roadway alignment are inadequate (29). The basis for determining structural and functional adequacy is the condition and appraisal data items (items 58-72) contained on the Structure Inventory and Appraisal Sheet (82). Condition codes indicate the condition rating associated with an inspection of a specific bridge structural component, while appraisal codes evaluate a bridge with relation to the highway system being served (12). Condition rating items include deck condition, superstructure condition, and substructure condition (28). Table 4-1 provides the possible condition rating codes, which range from 9 (the highest) to 0 (the lowest). Appraisal data items include the overall bridge structural condition, the relationship of the bridge to the approach highway width, the adequacy of the

TABLE 4-1

CONDITION RATING SCALE (28)

Rating	Descriptions
N	Not applicable
9	New condition
8	Good condition - no repairs needed
7	Generally good condition - potential exists for minor maintenance
6	Fair condition - potential exists for major maintenance
5	Generally fair condition - potential exists for minor rehabilitation
4	Marginal condition - potential exists for major rehabilitation
3	Poor condition - repair or rehabilitation required immediately
2	Critical condition - the need for repair or rehabilitation is urgent. Facility should be closed until the indicated repair is complete.
1	Critical condition - facility is closed. Study should determine the feasibility for repair
0	Critical condition - facility is closed and is beyond repair

vertical and horizontal underclearances, the safe load capacity, the waterway adequacy, and the adequacy of the alignment of the approach roadway (12). Table 4-2 contains the possible appraisal rating codes, again with a range of 9 to 0. Using these condition and appraisal rating as a basis for evaluation, Table 4-3 provides the classification of ratings for deficient bridges (81). Based upon this NBI data, the 1983 resurfacing, restoration and rehabilitation needs on the Interstate federal system alone were estimated at $9.6 billion (1). Additionally, the NBI data indicates that the total bridge needs far exceed the funding level of the national program (Figure 4-2). Thus, the magnitude of bridge infrastructure deterioration is immense.

Certain trends and correlations can also be identified through the use of this NBI data. For instance, Figure 4-3 correlates the age of the bridges versus the percentage of which are deficient by decade (1). One recognizable trend is that the off-system bridges become deficient faster than the on-system bridges. As expected, the overall life span of these off-system is shorter than the on-system bridges. There is also a substantial number of bridges built before 1940 still in everyday use. These bridges are expected to need extensive maintenance, rehabilitation or replacement within the next decade or two. The NBI data has also indicated other trends or observations. For instance, by using the available NBI data, the magnitude of the bridge deterio ration problems caused by deicing salt applications in the

TABLE 4-2

APPRAISAL RATING SCALE (28)

N	Not applicable
9	Conditions superior to present desirable criteria
8	Conditions equal to present desirable criteria
7	Condition better than present minimum criteria
6	Condition equal to present minimum criteria
5	Condition somewhat better than minimum adequacy to tolerate being left in place as is
4	Condition meeting minumum tolerable limits to be left in place as is
3	Basically intolerable condition requiring high priority of repair
2	Basically intolerable condition requiring high priority of replacement
1	Immediate repair necessary to put back in service
0	Immediate replacement necessary to put back in serivce

TABLE 4-3

CLASSIFICATION OF RATINGS FOR DEFICIENT BRIDGES (81)

STRUCTURALLY DEFICIENT

CONDITION RATING OF 4 OR LESS FOR ONE OF THE FOLLOWING ITEMS:

- ITEM 58: DECK
- ITEM 59: SUPERSTRUCTURE
- ITEM 60: SUBSTRUCTURE
- ITEM 62: CULVERT AND RETAINING WALL

APPRAISAL RATING OF 2 OR LESS FOR ONE OF THE FOLLOWING ITEMS:

- ITEM 67: STRUCTURAL CONDITION
- ITEM 71: WATERWAY ADEQUACY

FUNCTIONALLY OBSOLETE

APPRAISAL RATING OF 3 OR LESS FOR ONE OF THE FOLLOWING ITEMS:

- ITEM 68: DECK GEOMETRY
- ITEM 69: UNDERCLEARANCE
- ITEM 72: APPROACH ROADWAY ALIGNMENT

APPRAISAL RATING OF 3 FOR ONE OF THE FOLLOWING ITEMS:

- ITEM 67: STRUCTURAL CONDITION
- ITEM 71: WATERWAY ADEQUACY

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1) ITEM 62 APPLIES ONLY IF LAST TWO DIGITS OF ITEM 43 ARE CODED 07 OR 19.

2) ITEM 71 APPLIES ONLY IF LAST DIGIT OF ITEM 42 IS CODED 0, 5,6,7, 8 OR 9.

3) ITEM 69 APPLIES ONLY IF THE LAST DIGIT OF ITEM 42 IS CODED 0, 1, 2, 4, 6, 7 OR 8.

FIGURE 4-2

COMPARISON BETWEEN FUNDING LEVELS AND NEEDS

FOR HIGHWAY BRIDGE REPLACEMENT AND REHABILITATION PROGRAM

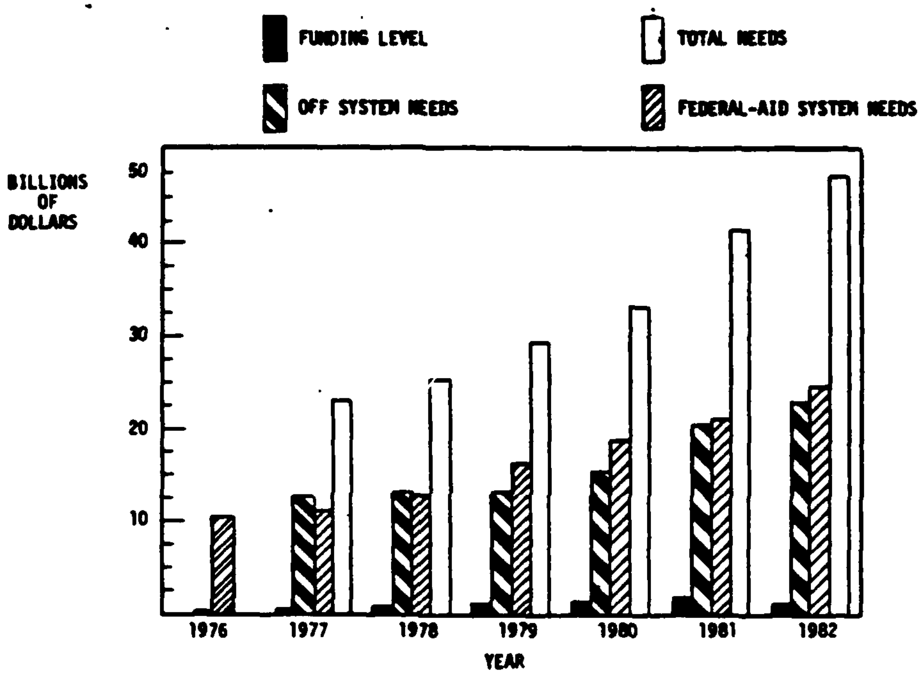


FIGURE 4-3

AGE DISTRIBUTION OF AMERICAN BRIDGES

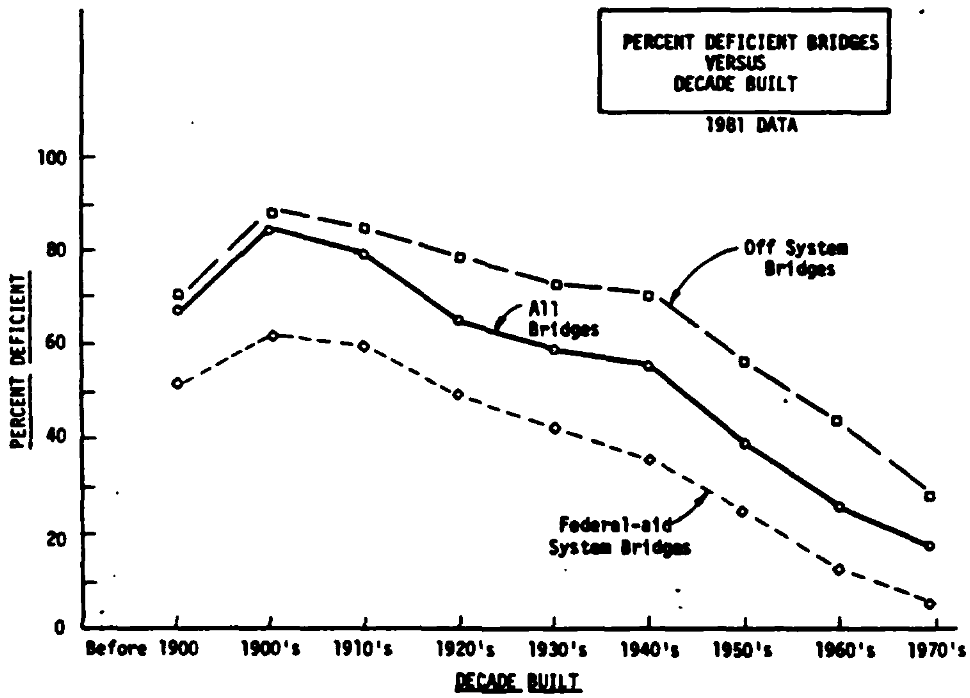
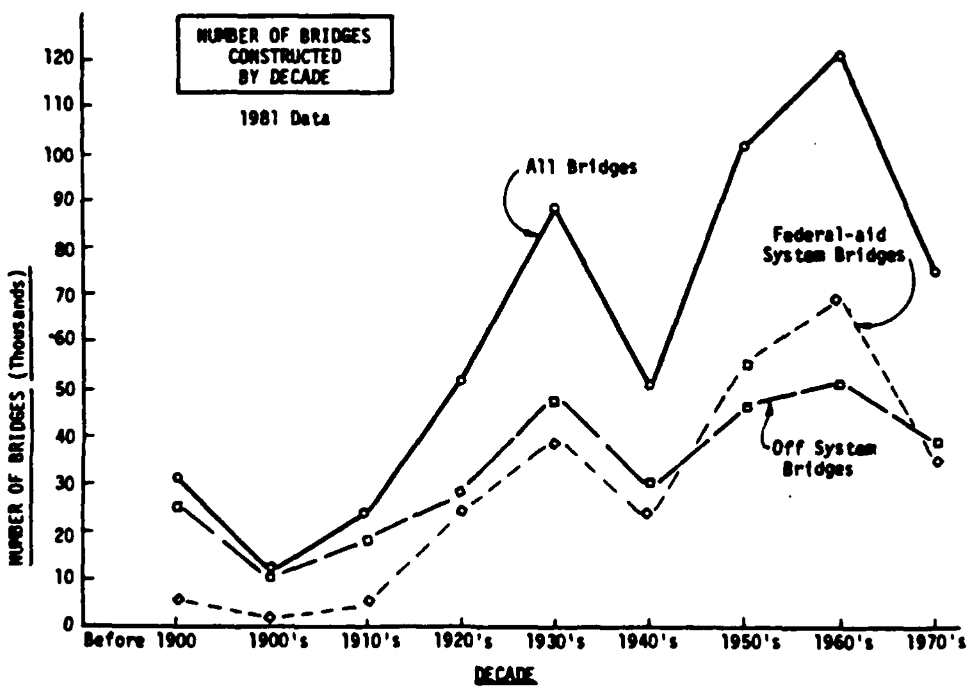


FIGURE 2



northern and moderate climate states can be quantified. In these areas, more than 39,000 bridges have a deck rating of 4 or less (1). Also, concrete bridge deck deterioration is more pronounced on steel girder bridges than concrete girder bridges and on continuous spans than non-continuous spans (12). Deterioration appears to increase with increasing span length and is more prevalent on skewed than non-skewed bridges (12). Insuffient drainage caused by inadequate slopes and grades also promotes deterioration. Furthermore, the type of protective system employed on the bridge deck affects the rate of deterioration (12). Thus, many of the factors affecting deterioration that were previously discussed in the previous chapter on concrete deterioration mechanisms have been validated by the use of this NBI data.

4.5 FEDERAL BRIDGE REPLACEMENT AND REHABILITATION PROGRAM

In addition to identifying the deficient bridges within the United States, the federal government also instituted a funding program to partially remedy this serious situation. Thus, Congress began the Special Bridge Replacement Program (SBRP) in 1970 and allocated a total of $816.5 million through FY 1978 for 1,606 bridges (29). As a result of the 1978 and 1982 Surface Transportation Assistance Act, the SBRP was replaced by the Highway Bridge Replacement and Rehabilitation Program (HBRRP) with an initial allocation of $4.2 billion for FY's 1979-1982 and $7.05 billion for FY's 1983-1986 (30). Under this program, the federal government will

provide financial assistance to states for projects designed to replace or rehabilitate structurally deficient bridges which are hazardous to the safety of motorists. The federal share of the cost is 80 percent and from 15 percent to 30 percent of the total amount allocated to each state is to be used on off-system bridges. Projects which are eligible for this program include (29,30):

- Total replacement of a structurally deficient or functionally obsolete bridges at or very close to the existing location. The replaced bridge must be closed permanently upon completion of the new bridge.

- Complete relocation of a structurally inadequate or functionally obsolete bridge with a new facility constructed in the same general traffic corridor.

- Major rehabilitation and partial replacement. When the substructure of a bridge is structurally inadequate to safely support a new superstructure conforming to current geometric and structural standards, the necessary substructure modifications and the superstructure construction to restore a bridge's structural integrity and correct major safety defects are eligible.

- Preliminary engineering and studies required to implement the bridge project.

- Initial inventory, inspection and classification of both on-system and off-system bridges.

Thus, this program offers greater flexibility in its implementation than the previous SBRP of the past.

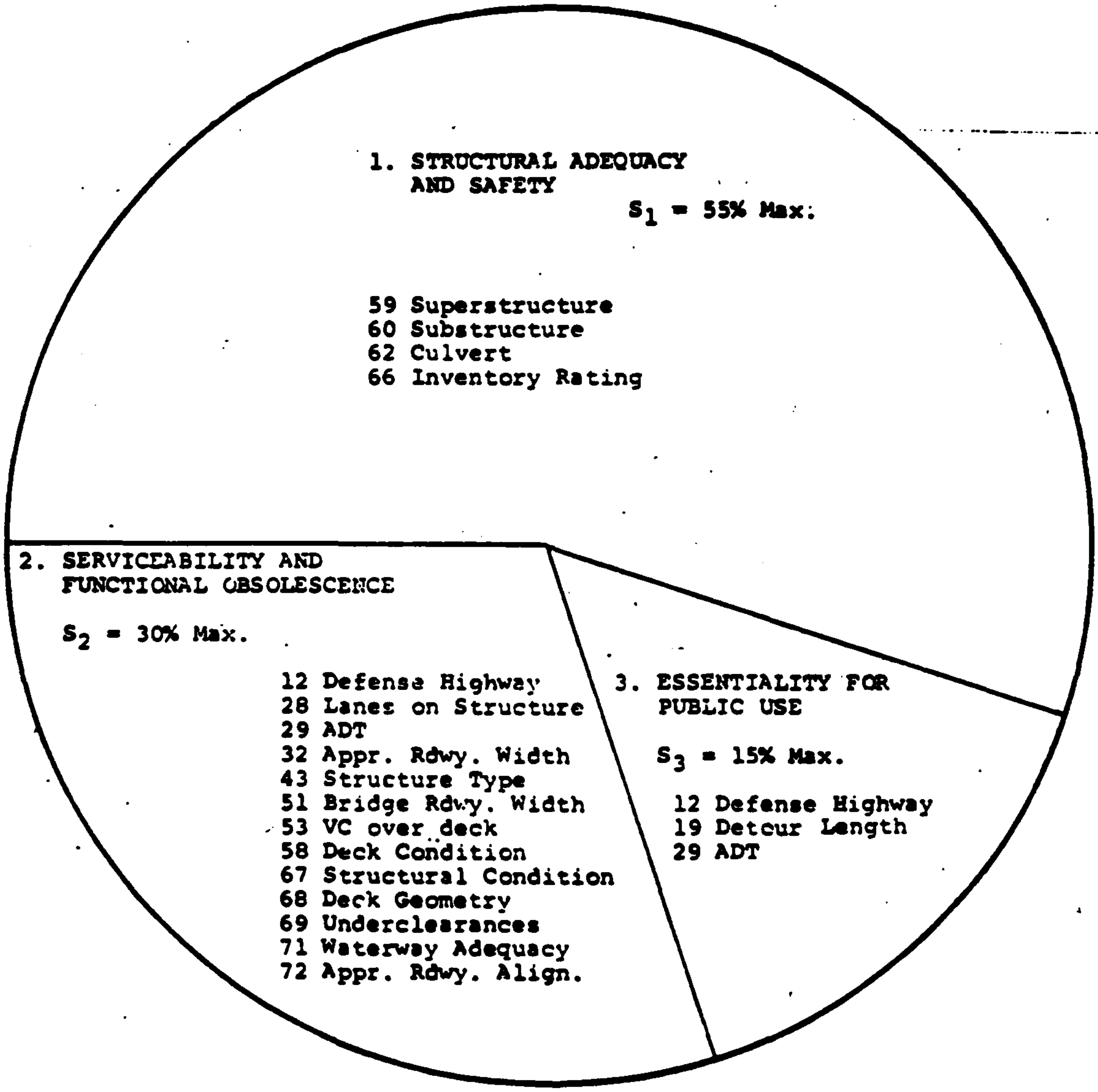
As a basis for evaluating submitted projects, a sufficiency rating will be computed for each bridge (29). There are three general categories and relative percentages which form the basis for calculating these sufficiency ratings (28,81):

- Structural adequacy and safety --- 55%
- Serviceability and functional obsolescence --- 30%
- Essentiality for public use --- 15%

Figure 4-4 provides a summary of these sufficiency rating factors and the associated NBI data elements. Bridges with a sufficiency rating of 100 are perfect bridges, while those with a rating of 0 are closed (29,81). Bridges with an overall sufficiency rating of 0-80 are considered deficient and eligible for rehabilitation (29). However, in order to qualify for federal aid, any rehabilitation must restore the structural integrity for a minimum period of 10 years. Those with an overall sufficiency rating less than 50 are eligible for replacement (29,81). Accordingly, a higher priority for replacement or rehabilitation is derived from a lower sufficiency code (1). As of the first quarter of 1985, $6,659 million has been obligated under HBRRP towards the nation's deficient bridges (29). As a part of these obligated funds, the New England Surface Transportation Infrastructure Consortium has received in excess of $ 200 million of these funds (29).

FIGURE 4-4

SUMMARY OF SUFFICIENCY RATING FACTORS (28)



4. SPECIAL REDUCTIONS

S_4 = 13% Max.

19 Detour Length
36 Traffic Safety Features
43 Structure Type, Main

SUFFICIENCY RATING = $S_1 + S_2 + S_3 - S_4$

Sufficiency Rating shall not be < 0 nor > 100

4.6 VALIDITY OF THE NBI DATA

A rational national bridge program depends upon both accurate and comprehensive bridge inventory data. On the surface, the NBI appears as a large and rich data set that will yield:

- a systematic inventory of the current conditions of the nation's bridges, and

- a basis for quantifying manpower, equipment, materials and funds to maintain the structural integrity and serviceability of the nation's bridges.

However, analysis of the quality and consistency of the data in the thesis work done by Busa (12) revealed deficiencies in two primary areas. First, illogical information for data items, such as bridge deck condition and bridge age, due to possible coding or recording errors were widely prevalent. Second, there were omissions of important structural attributes and maintenance history items. Also, there is no information on such important concrete bridge deck characteristics as air-entrainment, water-cement ratio, chloride content and depth of concrete cover. Finally, the subjective nature of these condition appraisals, relying primarily on visual observations rather than measurements, provides the potential for inconsistent interpretation and subsequent introduction of inaccurate data.

4.7 APPLICATION TO THE DECISION-MAKING PROCESS

The foundation for an overall effective bridge management system is the development, information collection, and extensive use of a very comprehensive data-base, which was previously illustrated in Figure 3-1 and will be explained in greater detail in Chapter Six. An important element of this comphrensive data-base is the bridge data file, as mandated by the National Bridge Inventory requirement. As previously mentioned, the NBI data consists of inventory data, inspection and appraisal data, and data related to future improvements. The inventory data associated with the NBI is constant and does normally change with time. Of the 58 inventory items in a NBI bridge record, 17 items relate to bridge identification, location and jurisdictional information and 31 items relate to bridge type, dimensions and geometric information. Although the inventory data is constant, the inspection and appraisal data that is part of the NBI varies with the bridge condition. Additionally, the 16 items related to future improvements provide the basic information required for establishing the criteria for a future bridge replacement or major rehabilitation effort. Included are such items as proposed bridge length, width and loading requirements, the date when the new bridge or rehabilitation effort should be completed, and the estimated cost of the effort. On its own merit, the requirements of the NBI are the minimum data that must be retained in order to meet federally mandated statutes and receive federal funds for bridge rehabilitation and

replacements. But, this data has far greater potential and uses as was stated previously in Section 4.3 of this chapter.

Many states, such as the New England states, have essentially established inventory and inspection programs which only gather this data. For example, except for the "remarks" portion associated with the NBI sheet (Figure 4-1), Vermont does not use the data for selecting candidate decks for rehabilitation or as an integral part of the decision-making process involving the deck repair versus replacement dilemma (99). In contrast, other states such as New Mexico, Pennsylvania and New York, have gathered additional information and applied both the NBI data and this additional information as a management tool in seven bridge management areas, as follows (53,57,58,64,74,90):

- Management of the bridge painting program,
- Management of the bridge inspection program,
- Management of the overweight vehicle permit program,
- Management of the routine maintenance program,
- Management of the major maintenance programs (to include deck repair and replacement),
- Preparation of the bridge needs estimate, and
- Preparation of budget and resource projections.

Furthermore, as shown in Table 4-4, this potential use of the NBI data is often unrealized, particularly by the northern New England states (90). Nevertheless, the National Bridge Inventory data is an important element of the overall data-

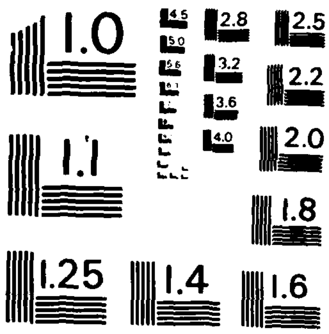
TABLE 4-4

CURRENT UTILIZATION OF NBI DATA IN BRIDGE MAINTENANCE MANAGEMENT IN NEW ENGLAND BY FUNCTIONAL AREA (90)

	ROUTINE MAINT PROGRAM	MAJOR MAINT PROGRAM	BRIDGE CAPACITY ESTIMATE	OVERLOAD ROUTING	RESOURCE FORECAST
MAINE	NONE	NONE	LIMITED	LIMITED	LIMITED
NEW HAMPSHIRE	NONE	NONE	NONE	LIMITED	NONE
VERMONT	NONE	NONE	LIMITED	LIMITED	NONE
MASSACHUSETTS	NONE	LIMITED	NONE	NONE	LIMITED
NEW YORK	YES	YES	YES	YES	YES
PENNSYLVANIA	YES	YES	YES	YES	YES
NEW MEXICO	YES	YES	YES	YES	YES

AD-A169 697 PRELIMINARY INVESTIGATION OF THE SYSTEMATIC APPROACH TO THE REPAIR VERSUS..(U) ARMY MILITARY PERSONNEL CENTER ALEXANDRIA VA C W PROTASIO 26 JUN 86 2/3

UNCLASSIFIED F/G 13/13 NL



MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

base that is essential in dealing with the deck repair/ replacement decision-making process. One use of this NBI data is to initially identify and prioritized the candidates for deck repair or replacement projects. An example use of the NBI for this purpose will be illustrated in Chapter Six. Once the nature of the deck condition is assessed using a detailed survey, there are many pertinent, updated NBI data items that can be used to evaluate and select a specific rehabilitation or replacement alternative. These items along with their NBI item number are provided in Table 4-5 (81). However, these items alone are normally not sufficient to adequately select the appropriate rehabilitation/ replacement strategy. Additional information, obtained from detailed deck inspections or surveys but not captured as an NBI data item, is also critical. These items, which need to be incorporated into the state's NBI data-base, are summarized in Table 4-6. Thus, an enhanced NBI data-base has an important role in the eventual selection between the deck repair and deck replacement option and the specific repair or replacement alternative (e.g., waterproof membrane) chosen.

4.8 SUMMARY AND CONCLUSIONS

Bridge inspection is an accepted and necessary part of the activities required to assure bridge safety. Primarily, as a result of this safety concern, the Federal government enacted the National Bridge Inventory and Inspection Program. This program identified critical inventory, condition and

TABLE 4-5

CURRENTLY AVAILABLE AND PERTINENT NBI DATA (28,90)

ITEM	NBI ITEM NO
Bypass Detour Length	19
Highway System	24
Year Built	27
Number of Lanes	28
ADT	29
Skew	37
Posting	41
Structure Length	43
Deck Width	49
Wearing Surface	57
Estimated Remaining Life	63
Proposed Improvement - Year	73
Proposed Improvement - Type	74

TABLE 4-6

RECOMMENDED ADDITIONAL NBI DATA

RESULTING FROM DETAILED DECK SURVEY (90)

ITEM	UNIT
Depth of Cover	inches
Delaminated Area	percentage of deck area
Chloride Contamination	lbs/cy
Spalled Area	percentage of deck area
Corrosion Potential	% deck > -.35
Cost to Repair Active Cracks	dollars $
Additional Cost due to Complex Deck	dollars $
Cost to Provide Electricity	dollars $
Aggregate Reactivity	yes/no

appraisal inspection items, defined sufficiency ratings and classifications for structurally deficient and functionally obsolete bridges, mandated minimum standards for inspection personnel and inspection intervals, and established a funding program to assist the states in improving these deteriorated bridges. This chapter has also identified a number of significant conclusions, related to the National Bridge Inventory and Inspection Program:

- the NBI data, in conjunction with other bridge-related data, has several bridge management uses beyond bridge safety, to include programs for bridge painting, bridge inspection, overweight vehicle permits, routine and major maintenance, bridge needs estimates, and budget and resource projections.

- the NBI data is an essential part of the overall bridge management data-base necessary for implementing a cost-effective and technically feasible decision related to the bridge deck repair versus replacement dilemma. Specifically, the data is important in initially identifying and prioritizing candidate projects and evaluating the technical feasibility of various repair and replacement alternatives.

- the bulk of the states, including the New England states, have failed to realize the potential of the NBI data.

- the NBI data must be creditable and accessible. Also, the data must be enhanced by additional items, obtained by detailed condition surveys, that are necessary to evaluate competing deck repair and replacement alternatives.

Thus, the NBI and Inspection Program has great potential and is a critical element of the repair/replacement decision-making process.

CHAPTER FIVE

BRIDGE DECK REPLACEMENT AND REHABILITATION ALTERNATIVES

5.1 INTRODUCTION

There has been a substantial amount of research into the problem of bridge deck deterioration. This research has resulted in a variety of rehabilitation/replacement alternatives. Thus, this chapter is intended to identify those techniques that are widely used, their associated performance and cost characteristics, and other relevant technical considerations. These rehabilitation alternatives include the following:

- Do nothing,
- Temporary repairs involving patching and epoxy injections,
- Dense concrete overlays,
- Waterproof membranes and bituminous wearing coat,
- Cathodic protection,
- Complete deck replacement, and
- Evaluation for possible bridge replacement.

As part of the deck repair/replacement decision-making process, an understanding of these specific rehabilitation/replacement alternatives is essential for the eventual identification of technically feasible alternatives, which then undergo a cost-effective analysis. Additionally, a well-maintained data-base that captures the identification, performance, and cost characteristics of these various alter-

natives is necessary. This data-base then must be updated to reflect subsequent performance and cost changes as well as new technology. Finally, the pertinent performance or cost characteristics obtained as a result of deck surveys or conclusions from studies of both construction and maintenance histories must be incorporated into the rehabilitation/replacement data-base file.

Prior to discussing these various deck rehabilitation/replacement alternatives, the wide variations in the cost associated with the same alternative must be understood. For individual cases, the average cost data associated with these alternatives has virtually no meaning. This point is clearly established in the NCHRP Synthesis of Highway Practice 57, as follows (105):

> Wide variations in costs can be expected for the same method of repair applied to different structures depending upon the size and location of the structure, traffic volumes, other work included in the same contract, scheduling, and the overall volume of construction work at the time of bidding.

Other factors, such as the availability, expertise and prevailing labor costs of contractors, the availability of specialized material and equipment, and the frequency of application, also influence this cost variability. Thus, the cost figures presented in Table 5-1 should not be used for evaluation of individual cases. These 1980 adjusted cost figures represent a compilation of average cost data from numerous sources, particularly Cady (17) and Park (81). Nevertheless, average cost figures are needed to evaluate life-cycle costs of alternative strategies for the eventual

TABLE 5-1

GENERAL COST AND SERVICE LIFE

ASSOCIATED WITH VARIOUS REPAIR ALTERNATIVES (17)*

ITEM, MATERIAL, OR ACTIVITY	ESTIMATED COST ($ PER SF)	ESTIMATED MAINTENANCE-FREE SERVICE LIFE (YR)
I. Bituminous Wearing Course Removal	2.00	
II. Concrete Removal (prep for overlays, rehabilitation or replacement)		
A. Scarification (1/4 in.)	0.61	
B. To top of upper rebar mat (Type 1)	8.10	
C. To 1 inch below top rebar mat (Type 2)	14.75	
D. Below type 2 to full depth (partial)(Type 3)	15.16	
E. Complete Deck Removal	11.56	
F. Deck modifications (raising expansion dams, scuppers, and backwalls)	1.00	
III. Conventional (unprotected) new concrete bridge deck	12.94	5
IV. New deck with epoxy-coated rebars	14.29	25
V. Cathodic Protection system (conductive-layer type)	5.26	10

* 1980 Adjusted cost figures

TABLE 5-1

GENERAL COST AND SERVICE LIFE

ASSOCIATED WITH VARIOUS REPAIR ALTERNATIVES (17)*

(CONTINUED)

ITEM, MATERIAL, OR ACTIVITY	ESTIMATED COST ($ PER SF)	ESTIMATED MAINTENANCE-FREE SERVICE LIFE (YR)
VI. Overlays (not including cost of scarifying or concrete removal)		
A. Latex-modified concrete (2 inch)	4.0	15a 20b
B. Low-slump dense concrete (2 inch)	4.77	15a 20b
C. Waterproof membrane w/ bituminous wearing course	2.11	8
VII. Repair, Patching and Surfacing for Rideability		
A. Bituminous concrete patching	1.23	0.67
B. Bituminous concrete wearing surface (1-1/2 inch thick)	0.44	5
C. Portland Cement concrete patching (Type 2 concrete removal	18.96	
D. Epoxy patching (2 inch thick)	42.08	
E. Delamination rebonding with epoxy	5.02	

a Only deteriorated concrete removed.

b All deteriorated and chloride-contaminated concrete removed.

development of broad policy guidelines. As a result of this wide and often state-specific variability in costs, each state must develop its own cost data-base in order to conduct engineering economic evaluations of competing rehabilitation/replacement strategies.

5.2 "DO NOTHING" ALTERNATIVE

The "do nothing" option implies that for reasons of obsolescence, advanced deterioration, impending reconstruction, etc., no scheduled activities are required except for emergencies or to keep the bridge safe to travel (57). Although this "do nothing" option is self-explanatory and involves minimal direct costs, this option must take into account user costs and generally the unacceptable level of service that can ultimately occur. Associated with this option is continued deck deterioration at a annual rate of increase estimated by Cady as 2.1 percent for unprotected bridge decks with an average 2-inch depth of concrete cover (15). Annual deterioration rates for decks with a protective system also need to be developed. Eventually, once deterioration exceeds a specified threshold percentage of the deck area, deck replacement is usually required. This percentage varies from state to state, e.g., ranging from 70 percent in Vermont to 25% in Rhode Island (99,102).

5.3 TEMPORARY REPAIRS

This type of repair is made when there is a need for

rapid restoration of the riding quality of the deck and either weather conditions or lack of funds preclude the use of other, more permanent techniques. In addition to improving the riding surface, the objective of such repairs, in some instances, is to retard the rate of further deterioration. There are currently several methods associated with temporary repairs, to include the primary ones of epoxy injection and patching (26,81,105).

5.3.1 EPOXY INJECTION

Epoxy injection is one cost-effective temporary repair method for extending the life of the deck. This technique, developed by the Kansas Department of Transportation in 1964, involves the injection of epoxy resin into delaminations that have not progressed to open spalling (105). The associated advantages of this technique is its ease of application and minimum disruption to traffic (6). The procedure as developed and used in Kansas consists of the following steps (26,81):

- Identifying delaminated areas,
- Sealing potential leakage points within the delamination with an epoxy paste,
- Locating the reinforcing steel,
- Drilling holes (using hollow-stemmed, carbide-tipped drill bits connected to a vacuum cleaner), missing the top steel reinforcement, to a depth that is below the delamination,
- Injecting epoxy into the delamination under pressure

using mortor-driven pumps; polymer concrete has been used with mixed success; and

- Scraping up excess epoxy and sprinkling exposed epoxy with sand.

Corings of bridge decks have shown that the epoxy injections are effective and achieve good crack penetration (105). Nevertheless, epoxy injections are no more than a continuing maintenance method for extending the life of the deck until such time that permanent rehabilitation can occur (26). Thus, this technique does not prevent the subsequent development of further deterioration (26,105). Furthermore, if cathodic protection is being considered as a permanent rehabilitation technique, epoxy injection should not be used (105). The epoxy would insulate the underlying steel from the cathodic protection circuit.

5.3.2 PATCHING

Patching repairs are essentially short-term solutions that repair the surface distress of the deck or improve the riding quality until a more adequate and permanent repair is undertaken (6,26). In some situations, the availability of funds or the weather may preclude the immediate use of other repair techniques (26). Normally, a distinction is made between temporary and permanent patches. Essentially, the temporary patch (local patching) usually involve the filling of the spalled area with a repair material, such as a cold-mix asphalt or, occasionally, a more durable hot-mix asphalt.

that requires no significant surface preparation prior to placement (26,105). These patches may be required to last through the winter months and may have to be replaced several times.

A permanent patch repair or partial restoration is often used to repair surface distress until either rehabilitation or replacement is possible. However, these permanent patches offer primarily cosmetic solutions to spalled deck conditions Moreover, these patches are likely to last no more than two or three years and actually accelerate the deterioration of adjacent areas (26,105). The basic steps associated with a permanent patch repair include (26,81):

- visual identification of distress surface area, occasionally supplemented by delamination detection.

- saw cut to a depth of 1 or 2 inches around the spall or delamination.

- removal of the deteriorated concrete using chipping hammers.

- cleaning the exposed reinforcing steel via wire brushing or sand- or waterblasting; particles, dirt, and surface oils must be eliminated.

- application of a bonding agent; for a polymer modified concrete used as a patching material, a bonding agent may not be required.

- application and curing of the repair material.

In practice the existing concrete is removed to at least the level of the top reinforcing steel and frequently removed to

an inch or so below the top reinforcing steel (26,105). Jackhammers in the 30-pound class or lower are recommended for the removal of the upper layer of deteriorated concrete, and chipping hammers in the 5-pound class or lower are recommended for removing the concrete around the reinforcing steel (26,81). Additionally, many state transportation agencies divide concrete removal into the following categories for payment (26):

- deck scarification to a depth of 1/4 inch,
- concrete removal to the level of the top mat, and
- concrete removal below the top mat.

After the concrete is removed, any exposed reinforcing steel is cleaned, a bonding agent is applied that consists of either a cement paste (50/50 cement-water) or an epoxy bonding agent, and the repair material is placed (26). Conventional portland cement is the material most widely used for patching the deck (6,81). Other patching materials include low-slump, high-density concrete based materials, latex-modified concrete, shotcrete (a form of portland cement sprayed with a gun), and epoxies (6). Patches that are well-supported by the underlying deck should be cured until the material has a compressive strength of at least 1000 psi prior to opening the deck area to traffic (6).

As previously mentioned, no patch can be expected to last but a few years on a corroding deck. Moreover, the placing of a patch changes the chloride, moisture and oxygen

content around the steel in the patched area (81). If the patch contains chlorides, a strong anoidic area may be created, quickly resulting in corrosion at the patch area (6,105). If spalled and delaminated concrete has been removed and the patch material does not promote corrosion of the reinforcing steel, the new patch may become a strong cathodic area (6,105). This ultimately induces rapid deterioration in adjacent, unrepaired areas of the deck.

A 1982 FHWA survey of state transportation agencies indicated that 41 states are using concrete removal and replacement as a repair method (26). Furthermore, 22 state transportation agencies reported that concrete removal and replacement is one of the most effective rehabilitation techniques with 12 agencies expecting to extend service life of the deck by 20 years or more (26). However, despite the quick restoration in the riding quality of the deck at a low cost and with minimum traffic disruptions, patches alone will not solve corrosion-induced deterioration and even permanent patches should not last more than 5 years (26,105). A summary of the associated cost components for temporary repairs is contained at Table 5-2.

5.4 TOTAL RESTORATION AND APPLICATION OF PROTECTIVE SYSTEM

The local patching and partial patching repairs previously discussed essentially provided short-term solutions that maintained an acceptable riding surface. However, for total restoration, a certain depth of the entire deck

TABLE 5-2

COMPONENT COST ASSOCIATED WITH TEMPORARY REPAIRS

-- PATCHING AND EPOXY INJECTIONS (17)*

ITEM, MATERIAL, OR ACTIVITY	ESTIMATED COST ($ PER SF)	ESTIMATED MAINTENANCE-FREE SERVICE LIFE (YR)
I. Bituminous Wearing Course Removal	2.00	
II. Concrete Removal (prep for overlays, rehabil-itation or replacement)		
A. Scarification (1/4 in.)	0.61	
B. To top of upper rebar mat (Type 1)	8.10	
C. To 1 inch below top rebar mat (Type 2)	14.75	
VII. Repair, Patching and Surfacing Rideability		
A. Bituminous concrete patching	1.23	0.67
B. Bituminous concrete wearing surface (1-1/2 inch thick)	0.44	5
C. Portland Cement concrete patching (Type 2 concrete removal)	18.96	
D. Epoxy patching (2 inch thick)	42.08	
E. Delamination rebonding with epoxy	5.02	

* 1980 Adjusted Cost Figures

is normally removed. Frequently, the deck is scarified to a depth of 1/4 inch followed by an overlay with chloride-free concrete (26). However, before the overlay is applied, all delaminated areas must be identified and removed to the level of sound concrete. Furthermore, research has indicated that permanent deck repair involves the removal of all chloride-contaminated concrete (i.e., concrete which is above the corrosion threshold of 2 pounds of chloride per cubic yard of concrete and has a electric potential of over .35 volts (81). If the area of unsound concrete extends deeper than 50 percent of the original slab, the State agency should consider replacement of the full deck (26). After application of the overlay, an acceptable protective system is then applied. These protective systems include dense concrete overlays, waterproof membranes with a bituminous wearing course, and cathodic protection (26,38,81).

As previously mentioned, total restoration which involves the removal of part but not all of the chloride-contaminated concrete is normally self defeating due to the large cathodic zones created. Nevertheless, the cost for removal of the chloride-contaminated concrete or the complete deck replacement may exceed the funding resources of many state transportation agencies (26,81). Therefore, the Federal Highway Administration permits the use of experimental cost-effective reconstruction techniques, whereby not all of the chloride-contaminated concrete is removed if it is otherwise sound

(26,81). Table 5-3 illustrates the allowable experimental cost-effective reconstruction techniques that are eligible for federal funding in accordance with the Federal Bridge Rehabilitation and Replacement Program. The sections that follow will highlight the performance and cost characteristics associated with the forementioned protective systems.

5.5 CONCRETE OVERLAYS

One of the most effective ways of prolonging the service life of a bridge deck has been the application of a thin concrete overlay. These concrete overlays may be applied as the second stage of construction on a new deck, as preventive maintenance on a deck that has been open to traffic for a short period of time but was built without a protective system, or in the rehabilitation of existing, deteriorated decks (6,26,105). The purpose of this deck protection system is to reduce the chloride penetration to the the reinforcing steel and thus limit the extent of possible corrosion (38). Moreover, there are several significant advantages associated with the application of a concrete overlay (105):

- The overlay can be tailored-made to provide required thickness for strength and durability.

- The overlay serves as an integral component in the load-carrying capacity of the deck.

- The overlay, when the concrete is properly consolidated, is effective in delaying and reducing chloride ion

TABLE 5-3

ACCEPTABLE RESTORATION PROCEDURES

FOR FEDERAL-AID PARTICIPATION (82)

CATEGORY	PROCEDURES	ACCEPTABLE PERMANENT RESTORATION	EXPERIMENTAL COST EFFECTIVE RESTORATION (Estimated Extended Life 10 to 15 years)
Structurally Inadequate		Complete Deck Replacement (Unless restorable)	
Extensive Deck Deterioration # 1	Required Restoration Work	Complete Deck Replacement	Removal of all deteriorated concrete. Follow the repair procedure* approved for the protective system selected.
	Testing	Steps #1 thru #5 as necessary Probably only Steps #1 & #2	Steps #1 & #2 only. (All steps on the first 5 plus 10% of the remaining decks)
	Suggested Protective Systems	Membrane w/ac overlay Two Course Iowa System or Latex Modified Concrete Cathodic Protection Epoxy Coated Rebars	Membrane w/ac overlay Cathodic Protection Iowa System or Latex Modified Concrete
Moderate Deck Deterioration # 2		Same as for Category #1 above OR Same as for Category #3 below as determined by the State	Same as for Category #1 above
Light Deck Deterioration # 3	Required Restoration Work	Removal and replacement of all areas of deterioration and chloride contaminated concrete as determined by corrosion potentials and/or chloride sampling. (Less than 5% of deck area)	Same as for Category #1 above NOTE: For this category of condition permanent restoration is strongly recommended.
	Testing	Steps #1 thru #5	Steps #1 & #2 only. (All steps on the first 5 plus 10% of the remaining decks)
	Suggested Protective Systems	Membrane w/ac overlay Cathodic Protection Iowa System Latex Modified Concrete	Membrane w/ac overlay Cathodic Protection Iowa System Latex Modified Concrete

TESTING STEPS:
1. Visual
2. Delamination
3. Electrical Potentials
4. Depth of Cover
5. Chloride Content

* (Park, 1980) (7).

penetration.

- The overlay allows vapor exchange between the concrete and the environment.

- The overlay is thermally compatible with the base concrete and absorbs less solar radiation than an asphalt overlay.

- The overlay provides a smooth riding surface.

- High quality aggregates in the concrete overlay mixture can enhance wear and skid resistance.

- In new construction, the overlay ensures adequate cover of the reinforcing steel.

- In repair work, the overlay will fill in areas of concrete removal without the need for a separate placing operation.

Although several different types of concrete containing various additives have been used as concrete overlays, the overwhelming majority of concrete overlays consist of the following (26,38,81):

- low-slump, monolithic concrete overlays, and

- latex-modified concrete overlays.

Generally, these two overlay systems have been widely used. For instance, a 1982 FHWA survey indicated that 39 states used one or both of these overlay systems for rehabilitation work and over 30 states will allow one or the other to be used for new deck construction (26). However, there appears to be a decline in the use of both systems on new deck construction. The contributing factors for this decline

include the high cost as well as the failures resulting from poor construction practices and/or lack of quality control by the contracting agency (26). Moreover, there appears to be no significant performance differences between these two overlay systems. Specific features of each overlay system, to include application procedures, service performance and cost, will now be addressed.

5.5.1 LOW-SLUMP, MONOLITHIC CONCRETE OVERLAY (IOWA METHOD)

A low-slump, monolithic concrete overlay, commonly referred to as the "Iowa Method", is a widely used and acceptable technique for deck protection. A 1982 FHWA survey indicated this method was practiced in 31 states with 22 state transportation agencies identifying this technique as one of the most effective protection methods in new deck construction as well as rehabilitation treatment (26). Essentially, this technique consists of placing a low-slump, high-density, high-strength, 2-inch concrete layer over a prepared deck as part of rehabilitation or as a 2-inch thick top layer as part of two-stage construction in new decks (6). Concrete used in this method has a low water-cement ratio of 0.328, a low slump requirement of 3/4 $\pm$ 1/4 inch, a cement factor in the range of 8 to 9 sacks per cubic yard, and a 6 percent air-entrained agent (6,26,81,105). With both proper mixing and placing, such an application greatly reduces the intrusion of chloride ions and moisture (6,26,38). Additionally, this technique also strengthens the bridge deck,

achieving compressive strengths up to 9000 psi (6).

The proper preparation of the deck for a concrete overlay is vital to a good bond between the resurfacing and the existing deck (6,26,81). When used in bridge deck repairs, the method first requires scarifying or the minimal removal of 1/4 inch or more of the existing wearing surface to eliminate contaminants and dirt (6,81,105). Additionally, spalled or delaminated concrete must be removed to the reinforcement layer which is cleaned. This cleaning process involves either sand- or waterblasting the concrete surface and the exposed reinforcing steel no more than 24 hours prior to the concrete placement (81,105). Then a bonding grout, consisting of equal parts by weight of portland cement and sand and mixed with enough water to form a stiff slurry, is evenly applied over the entire deck surface (6,26,81,105). Special care must be taken by project personnel to ensure that the grout does not dry out before the new concrete is placed. This often necessitates mixing the grout at the job site using a standard paddle mixer (26,81). Additionally, the mixing of the low-slump concrete, using either stationary paddle mixers or mobile continuous mixers, must be performed at the job site in order to minimize delays and also avoid the difficulties associated with transporting low-slump concrete (105). A heavy, vibrating screed should be used to ensure adequate consolidation of the mix (6,26). Some hand-finishing may then be necessary, particularly in the gutter line region, for a tight, uniform surface (81). For a skid-resistant

surface, transverse texturing can be achieved with a wire comb (26). After placement of the concrete, a wet-burlap cure is required for at least 72 hours (6,26,81,105). During the first 24 hours, the burlap must be kept continuously wet; after that the wet burlap can be covered with a waterproof covering, such as a polyethylene film, to hold in the moisture. Proper curing ensures sufficient water for hydration of the cement and prevents shrinkage, cracking and curling that would break the bond (26). Also, a minimum compression strength of 3000 psi is suggested before the bridge deck is opened to traffic (26). When the overlay is cured and dried, an additional protection of linseed oil may then be applied.

During the two-stage new construction or replacement of a bridge deck, all previously mentioned procedures are followed except for the elimination of: removal of existing deterioration concrete and scarifying the concrete surface to remove 1/4 inch (105). When the deck has been open for traffic prior to the application of the two-inch thick top layer, scarifying the concrete surface to remove 1/4 inch is then required.

Although this low-slump, monolithic concrete overlay method uses inexpensive materials, both labor and specialized equipment costs are high (6). Additionally, skilled contractors and inspectors are required to guarantee that the overlays are placed according to proper procedures (6,81). With regards to performance, low-slump monolithic concrete over-

lays exhibit good bonding between old and new decks, high durability, and effective resistance to chloride penetration (6,26,81,105). There is, however, a direct link between the extent of continued corrosion activity and the removal of contaminated concrete prior to overlay placement (81). Also, the low-slump, monolithic concrete overlays are susceptible to cracking and local bond failure as a result of inadequate surface preparation (6,105). A summary of these advantages and disadvantages is contained in Table 5-4.

5.5.2 LATEX-MODIFIED CONCRETE OVERLAY

Similar to the low-slump monolithic concrete overlay (Iowa method), the placement of a latex-modified concrete overlay is an acceptable practice for both new deck construction as well as a rehabilitation treatment. A recent FHWA survey indicated that latex overlays were used by 33 states as a rehabilitation technique (26). Additionally, 22 states indicated that this technique was one of the most effective techniques which will extend the service life of the deck anywhere from 10 to 20 years (26). Latex-modified concrete consists of a cement factor of 7 to 8 sacks per cubic yard, a water-cement ratio of 0.35 and a slump of 4 to 6 inches (6,26,81,105). Latex, usually in the emulsion form, is added at the rate of 24.5 gallons per cubic yard, which includes 12.25 gallons of water (26). This latex emulsion is essentially a collodial dispersion of synthetic rubber particles (6). Although these rubber particles may include polyvinyl

TABLE 5-4

ADVANTAGES AND DISADVANTAGES ASSOCIATED WITH

LOW-SLUMP MONOLITHIC CONCRETE OVERLAY

ADVANTAGES	DISADVANTAGES
1. Increased impermeability	1. Very fast set
2. Increased strength (structural component of deck slab)	2. Requires close supervision in installation
3. Long Service Life	3. Requires bonding grout
4. Inexpensive materials	4. Not suitable for decks with complex geometry
5. Many qualified contractors (depending upon region of the country)	5. Incapable of arresting active ccorrosion
	6. Expensive labor and equipment
	7. Poor skid resistance
	8. Unable to bridge moving cracks

acetates, acrylics, and vinylidene chloride, the only latex particles approved for federal-aid work and widely used is styrene butadiene (6,81). These latex particles coat the portland cement particles to increase both strength and impermeability to chloride solutions (6,81,105).

The deck preparation associated with this technique is the same as that for the "Iowa Method". However, the principal differences in construction from the "Iowa Method" are summarized as follows (6,81,105):

- Prior to overlay placement, the deck must be kept wet at least one hour;
- A separate bonding agent is not always used;
- Mixing equipment must be able to store and disperse the latex material;
- Latex-modified concrete has a high slump (5 inches versus 3/4 inch), is not air-entrained, and involves conventional deck finishing equipment;
- A combination of wet and dried curing is required; and
- The thickness of the overlay is usually slightly less (normally 1/2 inch) than for low-slump concrete.

A bonding grout is required prior to placing the mix. This grout can be obtained by separating the course aggregate from the latex-modified concrete mix and using the remaining water, sand, cement, and latex paste (26). This grout must be thick enough so that when this bonding grout is scrubbed into the prewetted, prepared surface with a stiff brush, the coating

will be thin and even but will not run or puddle. Also special care should be taken to ensure that the grout does not dry out prior to placing the new concrete.

The recommended thickness of the latex overlay is 1-3/4 inches (26,105). However, during total restoration, increasing the thickness beyond this recommended value to obtain adequate cover over the reinforcing steel may be more cost effective. Essentially, the pouring of the overlay concrete is straightforward except on steep grades and cross-falls where the latex-modified concrete tends to flow (6,105). The surface can be finished with a rail-mounted finishing machine which produces a high quality riding surface (26). Transverse texturing of the surface can be achieved with a wire comb, and most specifications require texturing grooves to be 1/8 inch to 3/16 inch deep at an average spacing of 1/2 to 2 inch (26). After finishing operations have been completed, a wet burlap should be placed on the deck surface as soon as the surface can safely support this weight. The minimum curing time is 24 hours of wet curing followed by 72 hours of air curing to allow the latex particles to coalesce into a film (81).

Although latex-modified concrete uses expensive materials, conventional machine usage reduces labor and equipment costs as well as the need for specialized knowledge (6,105). Additionally, this rehabilitation technique can perform satisfactorily on grades greater than 4 percent and

on areas where the pavement surfaces are subjected to shear forces created by rapid changes in the velocity or direction of traffic (38). Nevertheless, the presence of random or map cracks can occur within hours after placement due to high winds or temperature conditions and slumps greater than 5 inches (6,81,105). Transverse cracks that penetrate through the full depth of the overlay may also occur, primarily over piers on continuous deck slabs (81). Moreover, testing of latex-modified concrete overlay, in such places as Minnesota, have indicated good performance with respect to bonding between old and new decks, durability, and resistance to chloride penetration (75). Nevertheless, there is significant evidence that corrosion activity may continue beneath overlays placed on contaminated decks. Thus, the removal of contaminated concrete is essential prior to using this overlay technique. A summary of the advantages and disadvantages of this protective system is contained in Table 5-5.

5.5.3 SERVICE LIFE AND ESTIMATED COST

There is some disagreement as to the service life and the estimated cost associated with both the low-slump, monolithic concrete and latex-modified protective systems. The federal requirement for a deck protective system on federal-aid bridges is only a recent requirement. Moreover, to a large extent, these particular protective systems represent relatively new technology developed in the early 1960's. Thus, the ability to study a large number of concrete overlay

TABLE 5-5

ADVANTAGES AND DISADVANTAGES ASSOCIATED WITH

LATEX-MODIFIED CONCRETE OVERLAY

ADVANTAGES	DISADVANTAGES
1. Increased permeability	1. Not suitable for decks with complex geometry
2. Increased strength (structural component of deck slab)	2. Unable to bridge moving cracks
3. Long service life	3. Unable to provide good skid resistance
4. Use of conventional equipment	4. Unable to arrest active corrosion
5. Easily installed	5. Expensive materials
6. Does not require air entrainment	6. Subject to extensive map and random cracking
7. Satisfactory performance on grades in excess of 4 percent and deck areas subject to shear	

protective systems over a long period of time (15 to 20 years) is limited. Additionally, characteristic of all protective systems, the effectiveness and service life of concrete overlays are highly dependent upon proper construction and placement. Thus, the debatable service life of these protective systems is still an area of on-going research. Therefore, there are several estimates of the service life of concrete overlay protective systems, ranging from 10-20 years (17,26,70,90,81). Also, the relative cost of these protective systems varies extensively from state to state, based upon the availability of contractors and the historical development of the market in each state. Not surprisingly, those states with a history of low-slump, monolithic overlays exhibit lesser expense than latex-modified overlays and, vice versa. Table 5-6 summarizes both the service life and associated cost of both concrete overlay alternatives.

5.6 WATERPROOF MEMBRANES

Primarily in the Northeast, the use of waterproof membranes with a bituminous concrete wearing surface is extensively used on newly constructed decks as well as in rehabilitation work (26,81). As an example, in New Hampshire approximately 90%-95% of the bridges have a membrane protective system (100). Moreover, Vermont has performed extensive evaluations of membrane protective systems as part of a FHWA study (33,34). To a large degree, the extensive use of waterproof membrane systems is the result of a 1972 FHWA policy

TABLE 5-6

SERVICE LIFE AND COST ASSOCIATED WITH CONCRETE OVERLAYS

(LOW-SLUMP, MONOLITHIC CONCRETE OVERLAY AND LATEX-MODIFIED OVERLAY)

SERVICE LIFE		REPAIR COST		
		BITUMINOUS REMOVAL ($ PER SF)	CONCRETE REMOVAL AND REPAIR ($ PER SF)	CONCRETE OVERLAY APPLICATION ($ PER SF)
15 YEARS*	LOW SLUMP	2.0	33.71	4.77
20 YEARS**				
	LATEX-MODIFIED	2.0	33.71	4.09
		NEW CONSTRUCTION COST		
		BITUMINOUS REMOVAL ($ PER SF)	CONCRETE DECK REPLACEMENT ($ PER SF)	CONCRETE OVERLAY APPLICATION ($ PER SF)
	LOW SLUMP	2.0	24.50	4.77
	LATEX-MODIFIED	2.0	24.50	4.09

* Only deteriorated concrete removed.

** All deteriorated and chloride-contaminated concrete removed.

Concrete removal and repair assumes type 2 removal.

Concrete deck replacement assumes complete deck removal and new deck.

requiring that all federal-aid bridges be equipped with a deck protection system (6). However, the concept of a membrane is not a new phenomenom. Early membranes were built up on the deck in layers of bituminous material and reinforcement, such as fiberglass cloth (26). In the 1960's, membranes using epoxy resin systems with a wearing course appeared (26). In the 1970's, preformed membranes, which are unrolled and lapped on the deck surface, and liquid or applied-in-place membranes were developed (26). Ideally, these membranes are designed to effectively seal concrete decks against the intrusion of water and chlorides (6). Waterproof membranes, however, are not capable of arresting corrosion or strengthening the deck (6,26,38). Moreover, membranes can not be used on grades greater than 4 percent, at stopping points, or on bridges with maximum superelevation (106). Table 5-7 provides a summary of the advantages and disadvantages associated with the waterproof membranes. Despite the wide use of membranes, a 1982 FHWA survey indicated only 8 states listed this technique as an effective protective system (26). Additionally, 7 states characterized this protection system as an unsuccessful corrective measure with an expected life less than 10 years.

Performance characteristics that are essential for measuring membrane effectiveness and practicality include: impermeability, toughness, flexibility, stability, and other factors (6,33,106). Membrane impermeability, as measured by electrical resistance measurements, is a critical item. The

TABLE 5-7

ADVANTAGES AND DISADVANTAGES ASSOCIATED WITH

WATERPROOF MEMBRANE WITH BITUMINOUS WEARING SURFACE (6,81)

ADVANTAGES	DISADVANTAGES
1. Bridges moving cracks	1. Performance highly variable
2. Relatively impermeable	2. Will not stop corrosion activity
3. Provides good riding surface	3. Service life limited by wearing course
4. Applicable to any deck geometry	4. Nonstructural component of deck slab
5. Many qualified contractors	5. Not suitable for grades in excess of 4%, stopping points, or bridges with super-elevaltion
	6. Tendency to become brittle and to pinhole, blister and bubble
	7. Premature deterioration of bituminous overlay due to high traffic volume and inadequate drainage
	8. Poor bonding at the protection layers near expansion joints
	9. Replacement of membrane whenever surface removed

resistance of an effective dielectric membrane is high in effectively sealed areas, indicating that few paths exist for water and current flow (6,33,34,81). Thus, a reading greater than or equal to 500,000 ohms/ft^2 indicates excellent impermeability while a reading less than 100,000 ohms/ft^2 represents a poor seal (6,33,81,110). Another measurement of impermeability is a measurement of the chloride contamination content (33,34). Furthermore, the membrane must be durable to resist abrasion and impact and to transfer braking forces to the deck (6,111). Seals must be flexible over a wide range of temperatures in order to span cracks produced by temperature changes, concrete shrinkage, and traffic loadings (6,105,111). Sufficient stability is required to resist the lateral movement toward the wheel lines caused by repeated traffic loadings. Other critical performance characteristics include: adhesion to the concrete deck, resistance to age-induced deterioration, chemical inertness to highway contaminants, ease of application, and low cost (6,105).

5.6.1 TYPES OF MEMBRANE SYSTEMS

As previously mentioned, there are two basic types of membrane application: preformed membrane sheet systems and liquid or applied-in-place systems. The specific advantages and disadvantages of these methods are outlined in Table 5-8. In general, the preformed sheet system exhibits high quality control as a result of their factory construction and is less susceptible to blistering (6,33,34). However, this system

TABLE 5-8

COMPARISON OF WATERPROOF MEMBRANE SYSTEMS

PREFORMED SYSTEM

ADVANTAGES	DISADVANTAGES
1. High quality control and controlled membrane thickness and integrity	1. Labor intensive installation requiring expertise; laps necessary
2. Less susceptible to blistering	2. Difficulty in placement in curbed and rough decks
3. Good temperature flexibility	3. Vulnerable to quality of workmanship at curbs, expansion joints, and drainage areas
	4. Blisters must be repaired by puncturing and patching
	5. Tends to be more expensive

LIQUID SYSTEM

ADVANTAGES	DISADVANTAGES
1. Less expensive	1. High susceptibility to blistering during application and curing
2. Self-adhesive and better bonding	2. Extensive quality control to insure proper thickness and integrity and to detect presence of pinholes
3. Corrosion protection of drainage areas	3. Difficult to assure quality of 2-component materials and products which are hot applied
4. Usually applied in one course by spray or squeegee; no laps necessary	
5. Application independent of deck geometry	
6. Installation not affected by deck geometry	
7. Blisters and blowholes easily easily repaired in self-sealing materials	

requires labor intensive installation, with special care and expertise in placement on curved and rough decks and at curbs, expansion joints and drainage areas (6,33,105). Moreover, the problem of blisters forming in the preformed waterproof membranes does exist. Blisters that occur in the bituminous mix during paving are caused by air concentration trapped beneath the membrane during installation (6,26). These blisters can be prevented by puncturing the large air bubbles and then bonding the membrane to the deck after the air has been forced out the vent hole. Blisters are also caused by small concentrations of moisture which collect beneath the membrane (6,105). Such moisture may subsequently turn to a vapor or gas when exposed to the high temperature of the bituminous overlay. Post-construction blistering is also believed to be the result of moisture vapor pressures outgassing from the concrete, primarily due to poor bond between the deck and membrane (6,105).

Liquid systems are less expensive, primarily due to the seamless installation and easier repair of blistering (6,106). Moreover, this system is self-adhesive (resulting in a readily obtained bond and seal, particularly along the curb lines) and provides corrosion protection for drainage areas (6,106). Nevertheless, liquid systems require extensive quality control measures, such as careful field inspections to insure proper thickness and integrity (6,23,75). Liquid systems also exhibit high susceptibility to blistering during application and curing as a result of application of

membranes under high temperature conditions.

5.6.2 MEMBRANE APPLICATION

General application of both waterproof membrane systems is essentially the same. Initially, local patching of deteriorated portions of the concrete occurs. This is accomplished by saw-cutting the damaged or chlorided-contaminated concrete to the rebar level and then replacing the removed concrete with a low slump PCC (6,106). Placement of the waterproof membrane then occurs. Both systems require an asphaltic wearing course to provide the deck riding surface. Often an intermediate protective layer, such as roofing felt, is placed between the membrane and the wearing course to prevent damage during installation of the hot mix and to resist puncture of the membrane by aggregate particles under service conditions (6,26). The asphaltic wearing course should be a minimum of 2 inches thick and preferably 2 1/2 - 3 inches (26,81). If more than one lift is placed, the first lift should be 2 inches thick, resulting in a minimum total thickness greater than 2 inches (26). This wearing course has an effect on both the performance of the bridge deck and the economic life of the membrane. When the wearing course requires replacement, the membrane normally must also be replaced due to the difficulty in removing the existing wearing course with the membrane intact (6,38). Thus, the service life of the waterproof membrane is severely limited by the wearing course. The advantages and disadvantages of

using an asphalt wearing course are contained in Table 5-9.

A number of techniques to prevent blistering have been developed. One such technique involves sealing the deck pores to prevent air from escaping and blisters from forming when the membrane is applied (6,106). However, few of these sealants have proven effective. The second method is to apply the membrane under falling temperature conditions in order to eliminate the large temperature changes to which the deck is subjected (6,106). This technique involves the following options: preheating the deck with propane fired heaters, applying the membrane in the evening or at night, and using a black prime coat to preheat the deck by solar radiation (6). Each option attempts to eliminate the excessive temperature attained by the deck when a hot membrane is applied. In each case, the deck essentially cools off as the membrane cures. As a result of the special lighting equipment and traffic control meaures, potential safety hazards, and reduced curing rate due to lower temperatures, membrane application in the evening or at night is not particularly effective (6). The most effective technique is the application of a black prime coat, which has been effectively demonstrated in more than 100 laboratory and field experiments (6). Additionally, this technique may improve puncture resistance and allows extensive use of daylight hours for membrane application.

TABLE 5-9

ADVANTAGES AND DISADVANTAGES

OF BITUMINOUS WEARING COURSE (106)

ADVANTAGES	DISADVANTAGES
1. Provides a smooth riding surface	1. Adds dead load and is not a structural component
2. Reduces stress concentrations on concrete slab due to vehicular loading	2. Deterioration of the concrete cannot be detected until serious distress has occurred
	3. Must be replaced periodically every 5 to 15 years
	4. Asphalt absorbs solar radiation more rapidly than concrete, thus increasing number of frost cycles in winter months
	5. Porous and permeable nature of asphalt results in brine trapped on membrane surface
	6. Asphalt difficult to compact at curbs, joints, and deck drains; thus most porous at critical waterproofing areas
	7. Bonding of membrane and wearing surface difficult
	8. If leakage occurs through the membrane, water is trapped on deck and deterioration is accelerated
	9. Cracks in asphalt may be reflected through the membrane
	10. Additional cost factor

5.6.3 RESULTS OF STUDIES ON MEMBRANE EFFECTIVENESS

Extensive testing of membranes in Kansas, Minnesota, Colorado, and Vermont have surfaced some significant conclusions with regards to membrane effectiveness. For instance, Vermont testing of bridge deck membrane systems indicated that preformed sheet membranes provided the best overall performance as measured by the presence of contaminated chloride samples (33,34). The Minnesota study indicated that chloride penetration through membrane and bituminous overlay systems from one to several years old is minimal and is limited to the first (surface) 1/2- inch increment tested (75). On many decks, a significant portion of contaminated chloride samples occurred near the curb line (75). Additionally, membrane durability is more strongly influenced by traffic action and placement operations than by deck condition (23,33,34,75). In particular, a variety of membrane systems can be made to work if adequate time and effort is spent in the selection, design, and installation (75). Also, system deficiencies were encountered earlier and more frequently on membrane-bituminous systems exposed to high volume, heavy traffic (75). Moreover, when construction deficiencies exist, traffic action aggravates and magnifies their effect on system durability (75). Common construction deficiencies include: proper system placement according to the manufacturer's recommendations and proper treatment of drainage. Thus, contractor experience is a critical factor. Saturation

of the bituminous overlay appears to be a major contributing factor to early general deterioration (75). Moreover, the effectiveness of the membrane is limited by the performance of the wearing course (6,38,81). Many membrane overlays have been observed to exhibit premature deterioration, due primarily to the loss of cohesion between the aggregate and binder at the membrane/overlay interface and the subsequent instability and chucking (75). Conventional bituminous overlays on membrane systems experienced progressive deterioration after one to three years of service (23). This deterioration began soon after placement and was more severe on thin (less than two-inch thick) overlays subject to high volume (10,000 to 100,000 ADT) where inadequate drainage exists (6). Large temperature differentials between the top of the deck and the bottom of the overlay may result in poor bond (6,75). Initial overlay failure commonly occurs in the right wheel path of the driving lane and moves progressively toward the median on four lane systems (75). Finally, overlay deterioration appears to occur equally on liquid and preformed sheet systems (75).

5.6.4 SERVICE LIFE AND ESTIMATED COST

The installation of a waterproofing membrane is an acceptable protective system for both new construction and rehabilitation of an existing deck. However, in rehabilitation work which involves the removal of part but not all of the chloride contaminated concrete, the installation of a

waterproof membrane may be self-defeating, because it will do little to reduce the effects of corrosion (26). As a result, the life expectancy of this restoration procedures is limited to less than 10 years in these situations. Thus, as with other previously mentioned protective systems, the maximum effectiveness and service life associated with a waterproof membrane protective system occurs when all the chloride contaminated concrete is removed and the system is properly emplaced. Table 5-10 provides the service life and cost associated with this system.

5.7 CATHODIC PROTECTION

Cathodic protection is the only technological alternative that has the potential for arresting or halting the corrosion of the reinforcing steel of a bridge deck, thus preventing deterioration of new bridge decks and retarding the progress of deterioration in bridge decks already showing signs of distress (6,94,106,114,118). Advantages of this method include (114):

- Corrosion is completely stopped when cathodic protection is properly applied.
- The effectiveness of cathodic protection in arresting corrosion can be measured by simple, nondestructive electrical measurements.
- The cost of applying cathodic protection is a fraction of the replacement cost of the threatened bridge structure and is the least expensive means of providing long-term,

TABLE 5-10

SERVICE LIFE AND COST ASSOCIATED WITH WATERPROOF MEMBRANE PROTECTIVE SYSTEM

SERVICE LIFE	REPAIR COST		
	BITUMINOUS REMOVAL ($ PER SF)	CONCRETE REMOVAL AND REPAIR ($ PER SF)	WATERPROOF MEMBRANE W/ ASPHALT CVG ($ PER SF)
8 YEARS	2.0	33.71	2.11
	NEW CONSTRUCTION COST		
	BITUMINOUS REMOVAL ($ PER SF)	CONCRETE DECK REPLACEMENT ($ PER SF)	WATERPROOF MEMBRANE W/ ASPHALT CVG ($ PER SF)
	2.00	24.50	2.11

CONCRETE REMOVAL AND REPAIR APPLIES TO TYPE 2 REMOVAL.

CONCRETE DECK REPLACEMENT INCLUDES COMPLETE DECK REMOVAL AND NEW DECK.

maintenance-free service life for metal structures in corrosive environments.

Since cathodic protection can halt but not remove corrosion, it is effective on existing bridges only if they do not exhibit severe delamination or chloride contamination (6,81). The bridge decks must be structurally sound since the cathodic protection system does not provide any additional strengthening. Finally, considerable expertise in design, construction, monitoring and inspection are associated with this technique (6). Table 5-11 summarizes the advantages and disadvantages associated with cathodic protection.

5.7.1 APPLICATION PRINCIPLES

Cathodic protection of bridge decks, pioneered by Richard Stratfull of California in 1973, involves applying a flow of external current from any source to the reinforcing steel (6,26,81,94,106). This external current overcomes the internal current flow from the anoidic areas, halting the corrosion of the reinforcing steel. Two methods are generally used to transmit the protective current: sacrificial-anode systems and impressed-current systems (6,26,81,94). In the sacrificial-anode system, the threatened structure is made the cathode of an electrolyic corrosion cell with a more active metal as an anode (114). A metal electrode that is anodic to the metal of the structure is connected to the structure by a metallic conductor and is placed in the electrolyte with the structure, as shown in Figure 5-1

TABLE 5-11

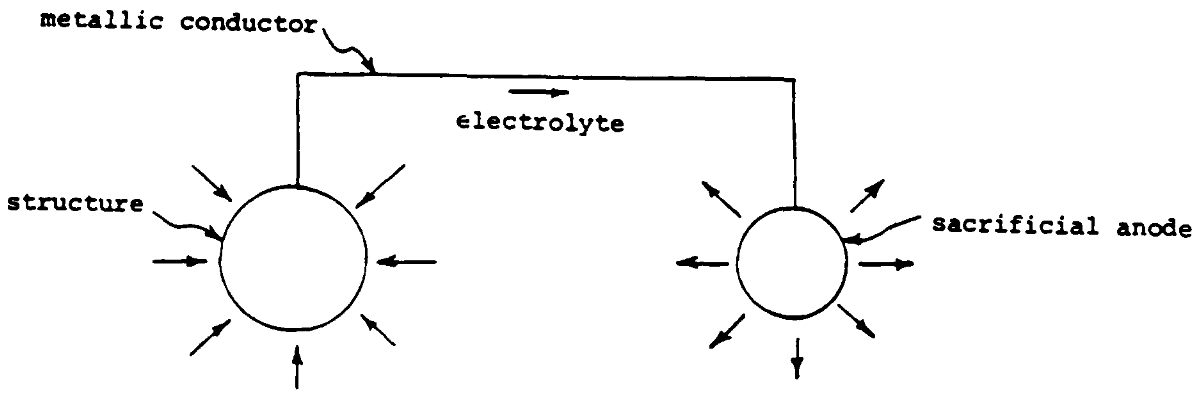
ADVANTAGES AND DISADVANTAGES

ASSOCIATED WITH CATHODIC PROTECTION (106)

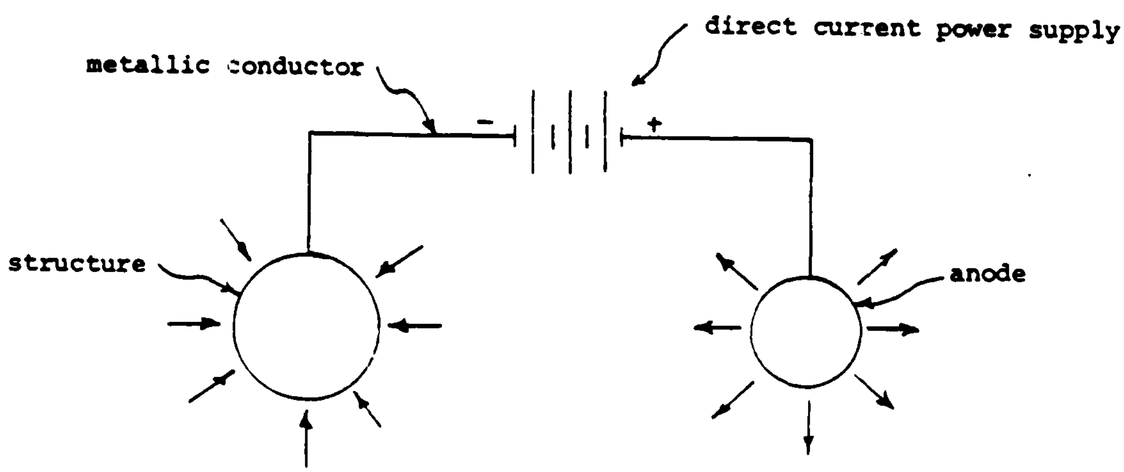
ADVANTAGES	DISADVANTAGES
1. Stops active corrosion	1. Presence of wearing course may accelerate freeze-thaw deterioration of the concrete
2. Can be used on decks with moving cracks	2. Nonstructural component of the deck slab
3. Provides good riding surface	3. Continuing maintenance procedure
4. Applicable to any deck geometry	4. Limited performance history
	5. Service life limited by wearing surface
	6. Specialized contractor and inspection required
	7. Electrical power source required

FIGURE 5-1

CATHODIC PROTECTION PRINCIPLES



SACRIFICIAL-ANODE CATHODIC PROTECTION



IMPRESSED-CURRENT CATHODIC PROTECTION

(6,114). The structure and the anode operate as a bimetallic corrosion cell. The corrosion is transferred from the structure to the anode, which is expendable and may be easily replaced (114). The driving potential for the current is the natural potential difference between the metal of the structure and the anode (6,94,114). Currently, magnesium and zinc are used as sacrificial anodes for the cathodic protection of steel reinforcement in concrete bridge decks.

The impressed-current system operates essentially in the same manner as the sacrificial-anode system, except that external power is provided to drive or impress the current into the structure receiving the protection (94,114). Thus, current flow is not dependent on the relative potentials of the anode and the metal of the structure. As a result, anodes are selected on the basis of their capability to conduct current and transmit it to the electrolyte with a minimum amount of corrosion to the anode (114). Carbon and high-silicon cast iron are the anode materials most often used (6,94,114). Although batteries and wind-driven generators have been used in remote areas, the most common source of protective current is the rectifier, which converts alternating power to direct-current power (114). The following sections provide a more detailed description of these protection methods, to include performance characteristics and the associated advantages and disadvantages of each method.

5.7.2 IMPRESSED-CURRENT CATHODIC PROTECTION OF BRIDGE DECKS

Regardless of the cathodic-protection method chosen, an essential parameter is an anode arrangement over the top rebar, which gives a uniform current flow of appropriate value to the rebar mat. With this as a criteria, the most promising method of cathodic protection of bridge decks is the impressed-current cathodic-protection design. In this design, an inert electrode is placed in contact with an electrically conductive asphaltic concrete, which is spread uniformily over the surface of the bridge deck (6,94,114). Examples of suitable types of anodes include a disk-shaped, 12-inch-diameter silicon-iron type and a continuous platinum-surfaced niobium wire of 0.063-inch diameter (114). The asphaltic concrete, ranging in thickness from 0.5 - 2 inches depending on anode choice and arrangement, is made electrically conductive by incorporating a carbonaceous material, such as coke breeze, within the concrete mix (6,94,114). The coke breeze, a secondary anode, is a good electronic conductor that permits the current to be distributed and introduced uniformly into the deck concrete. The implementation of this protection system includes (6,94,114):

- initially patching concrete as if in preparation of a membrane application;

- placing electrical anodes no more than 30 feet apart for the 2-inch thick conductive layer and up to 15 feet with a thinner .5-inch thick layer;

- covering the anodes with the electrically conductive asphalt-concrete overlay, which involves significant design changes in the elevation and dead load of the deck;

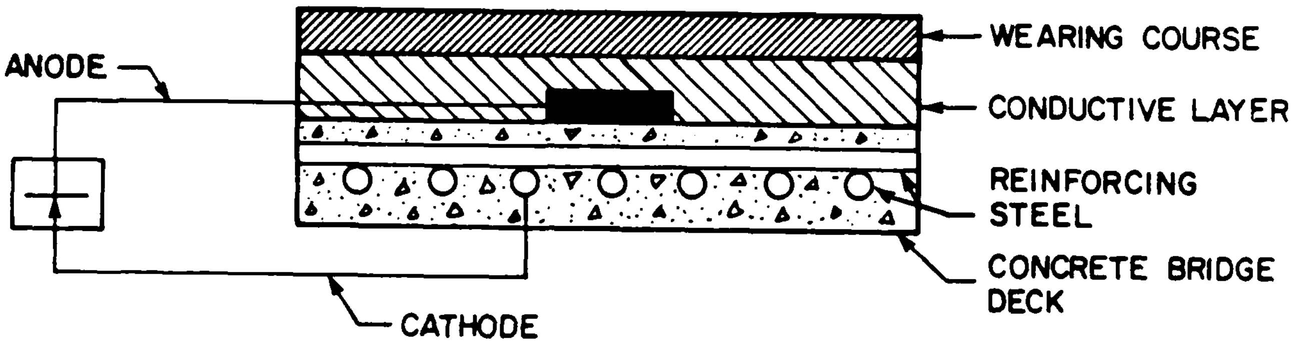
- paving the deck with a 2-inch conventional bituminous mixture in order to protect the coke-breeze asphaltic concrete by distributing wheel loads and providing resistance to rutting or shoving; and

- applying low-voltage, direct-current electricity to the deck from alternating-current rectifiers.

Testing has indicated that a minimum polarization potential value of -0.77 V to a copper-copper sulfate reference cell is a suitable cathodic-protection criterion (94,114). In order to avoid loss of bond between the concrete and the rebars resulting from overprotection of the steel, the maximum polarized potential value with the rebars in the bridge deck should be limited to -1.1 V to the copper-copper sulfate reference (94,114). This impressed-current cathodic protection arrangement of wearing course, conductive layer, etc. is illustrated in Figure 5-2. In constructing this cathodic system, the deck is divided into several zones, each to be controlled independently by reference cell potentials (26). In each zone, there is a cathodic system consisting of a string of strategically located anodes attached to precut wires that connect to the centrally located rectifier (26). The anode arrangement is crucial to insuring an even distribution of current throughout each zone.

FIGURE 5-2

IMPRESSED-CURRENT CATHODIC PROTECTION CIRCUIT (106)



Recently, identification of simple and less costly cathodic protection systems without an overlay and with minimum traffic interruptions have been developed (26). Both the MATCOR amd HARCO systems utilize platinum-clad anode wire placed in slots cuts into the deck surface at a spacing not to exceed two feet. The MATCOR system utilizes a 0.031-inch diameter platinum and niobium-clad, copper core wire placed in 1/2-inch x 1/2-inch slots, backfilled with a "conductive" grout. The HARCO system utilizes a 0.062-inch diameter platinum-clad, niobium core wire placed in a 3/4-inch wide and 1 1/4-inch deep slot. This slot is partially filled with Laresco DW-2 fine coke and topped with a flexible sealant.

5.7.3 SACRIFICIAL-ANODE CATHODIC PROTECTION OF BRIDGE DECKS

A second method of cathodic protection are the sacrificial-anode systems. These systems find their greatest use in remote areas where electrical line power for impressed current system is unavailable or too costly to supply (118). They may also be economically more attractive than impressed current systems where current requirements for cathodic protection are relatively low (118). In general, bridge decks which show low-to-moderate levels of corrosion and are subjected to only moderately aggressive environments should be considered candidates for these galvanic systems. Finally, the simplicity of the systems make them attractive in areas prone to vandalism where impressed current rectifiers and associated electronics are subject to possible damage (118).

Two sacrificial-anode system designs have been examined and tested as part of a National Cooperative Highway Research Program (118). The first system consists of commercially available ribbon zinc anodes placed in grooves cut into the deck at regular intervals (5 inches). A porous portland cement mortar is used as a stabilizing backfill. This portland mortar provides space into which corrosion products may expand, provides for low contact resistance, and more effectively distributes current from the ribbon anodes to the concrete matrix. The second system consists of perforated zinc anode sheets bedded on a 1/2-inch lift of similar porous mortar. An open-graded ("free draining") asphalt wearing course provides protection from physical damage and maintains a high moisture content at the original deck surface because of its ability to transport water rapidly.

Actual field study of these sacrificial-anode cathodic protection techniques indicated that these systems provided the levels of polarized potential and current density necessary for adequate cathodic protection (118). The perforated zinc sheet system delivers the highest and most consistent amount of polarization. Environmental factors, such as temperature, moisture and salt content, were found to play an important role in the functioning of these techniques (118). Highest current outputs and most negative potentials were encountered during warm, moist periods in mid-to-late spring. Under dry or cold conditions, current output decreases and

some polarization was lost. Nevertheless, it can be assumed that corrosion will be most active under those conditions conducive to maximum protection from the cathodic protection techniques.

5.7.4 COMPARISON OF SYSTEMS

There are inherent advantages and disadvantages associated with the two different systems of cathodic protection, the sacrificial-anode system and the impressed-current system (6,106,114,118). Relying on inherent galvanic potential, the sacrificial anodes result in low driving voltage and thus are restricted to environments of relatively low electrical resistivity. On the other hand, the impressed-current system can be designed to deliver large amounts of current at high voltage and, therefore, can be used in almost any environment. Thus, the impressed-current system, having a greater range of output and a longer service life than the sacrificial-anode system, is more commonly used. However, in the impressed-current system, the use of high current and voltage may result in nonuniform potentials and possible overprotection, which could adversely affect the bond between concrete and steel. An advantage of the sacrificial-anode system is that, when properly installed, the system may be expected to operate continuously without maintenance for the life of the anodes. Since the driving voltage is inherent and the currents and voltages are relatively small, the probability of system failure is small. The equipment used with the

impressed-current system is subject to deterioration and does require periodic maintenance and inspection. Thus, in this system, any flaw in the anode cable insulation can result in an interruption of the impressed current flow. Table 5-12 provides a comparison of these cathodic protection systems.

5.7.5 USAGE, SERVICE LIFE, AND COST FACTORS

Although the promotion of this technology is a high priority item within FHWA and installation of cathodic protection systems is encouraged, this protective system has had limited use in the United States. A 1982 FHWA survey indicated that only 12 states have installed the cathodic protection system (26). In each of these states, cathodic protection has proven to stop corrosion in salt contaminated structures regardless of the chloride content of the deck. The contributing factors for the limited use of cathodic protection include the initial cost, unfamiliar technology and the need for a conductive overlay which involves significant design changes in the elevation and dead load of the structure (26). Moreover, the cost of the cathodic protection is highly variable, often depending on the local availability of coke breeze. Table 5-13 provides the service life and associated cost of the cathodic protection system.

TABLE 5-12

COMPARISON OF CATHODIC PROTECTION SYSTEMS

SACRIFICIAL-ANODE

ADVANTAGES	DISADVANTAGES
1. Continuous operation over life of anodes	1. Low driving voltage
2. Low probability of system failure	2. Limited anode life
3. No danger of overprotection	3. Limited applications
4. Minimal maintenance	
5. Ideal for remote areas where electricity is unavailable or areas of high vandalism	

IMPRESSED CURRENT

ADVANTAGES	DISADVANTAGES
1. Applications in any environment	1. Possibility of over-protection, nonuniform potentials, decreased bond strength
2. High driving voltage	2. Susceptibility to power failures
3. Better anode durability	3. Thorough maintenance and monitoring required
	4. Conductive paving layer required
	5. Subject to vandalism and requires electricity at the site

TABLE 5-13

SERVICE LIFE AND COST ASSOCIATED

WITH CATHODIC PROTECTION

SERVICE LIFE	REPAIR COST		
	BITUMINOUS REMOVAL ($ PER SF)	CONCRETE REMOVAL AND REPAIR * ($ PER SF)	CATHODIC PROTECTION APPLICATION** ($ PER SF)
10 YEARS	2.0	33.71	5.26
	NEW CONSTRUCTION COST		
	BITUMINOUS REMOVAL ($ PER SF)	CONCRETE DECK REPLACEMENT ($ PER SF)	CATHODIC PROTECTION APPLICATION** ($ PER SF)
	2.0	24.50	5.26

* REMOVAL OF UNSOUND, DETERIORATED & DELAMINATED AREAS; REMOVAL OF ALL SOUND, CHLORIDE-CONTAMINATED AREAS IS NOT NECESSARY; CONCRETE REMOVAL IS TYPE 2.

** INCLUDES 2-INCH BITUMINOUS WEARING SURFACE.

5.8 COMPLETE DECK REPLACEMENT

As a result of excessive deterioration, the outcome of a cost-effectiveness analysis, cracking caused by reactive aggregates, or possibly adequacy requirements (e.g., a need for a wider deck), complete deck replacement may become necessary. In order to reduce the future deterioration of this replacement deck, the use of high-quality concrete, strict quality control and design specifications, good field construction practices, a low water-cement ratio (0.40), increased concrete cover for reinforcement steel (minimum of 2 inches), and air-entrainment are recommended. Although the use of higher strength concrete will likely add to the initial cost, this use has found to be cost-effective in terms of life cycle costs by providing protection against corrosion. Additionally, it is recommended that the minimum deck thickness should be 8-1/2 inches (6,81,106). The following protective systems are subsequently used to prevent early deterioration of the replacement concrete deck:

- epoxy coated reinforcing bars,
- dense concrete overlays,
- waterproof membranes with bituminous wearing course,
- cathodic protection, and
- double protection.

All of these protective systems, with the exception of the epoxy coated reinforcing bars and the double protection, have been previously discussed with respect to performance, cost and service life (Tables 5-2 to 5-13). Thus, the focus of

the next sections will be these newly identified protective systems.

5.8.1 EPOXY COATED REINFORCING BARS

Epoxy coated reinforcing bars can be used as a means of protecting new or replacement bridge decks from corrosion. The coating is effective in isolating the reinforcing bars from the corrosive consequences that water and chloride solutions affect upon exposed reinforcement (6). However, the bars do not improve the freeze-thaw durability of the concrete. Among the variety of potential coating materials, the coal-tar epoxy coatings are the most successful, primarily due to their strength, excellent bond characteristics, tolerance for poor cleaning, and short cure time (6). These epoxy coated bars are widely used in the top mat of new decks, in the barrier curbs, parapets, and the top of bridge seats under the joints in order to minimize corrosion damage (81). Moreover, the Illinois Department of Transportation assessed the cost of coating the bottom reinforcement mat of deck slabs as less than one percent the cost of the deck (81).

The process of epoxy coating rebars consists of blast cleaning them to a near white, heating them in an oven for 30 minutes at a temperature of approximately 450-470° F, and passing them through an electrostatic spray which applies the charged dry epoxy powder to the heated bars (81). This process provides 7 $\pm$ 2 mils of coating, thus protecting the bars

from the corrosive elements of oxygen, moisture, and chloride (6). The bars are cooled by either air or water quenching, subsequently inspected for cracks and pinholes, and repaired with a liquid epoxy.

5.8.2 DOUBLE PROTECTION

Bridges that are exposed to high traffic volumes and heavy use of deicing chemicals may be protected by using multiple protective systems. Generally, this implies a deck with epoxy coated rebars in the top mat covered with another protective overlay system. For instance, the Ontario Ministry of Transportation uses epoxy bars with a conventional waterproofing system, finding this to be their least expensive alternative (81). The cost of this system included the total replacement cost of a waterproof membrane with a bituminous wearing course every 15 years. As an alternative overlay system, the dense concrete overlays have as disadvantages high initial costs and the restriction of constructing these overlays in lower temperatures (81). However, a number of states, such as Pennsylvania, use the double protective system of epoxy coated rebars and dense concrete overlays, primarily as a result of the maintenance free nature and greater effectiveness of these concrete overlays (13,81). Costs and service life associated with epoxy coated reinforcing bars and double protection are contained in Table 5-14.

TABLE 5-14

SERVICE LIFE AND COST ASSOCIATED

WITH COMPLETE DECK REPLACEMENT USING

EPOXY COATED REBARS AND DOUBLE PROTECTION

SERVICE LIFE	NEW CONSTRUCTION COST			
EPOXY-COATED REBARS	BITUMINOUS REMOVAL ($ PER SF)	CONCRETE DECK REMOVAL ($ PER SF)	CONCRETE DECK WITH EPOXY REBARS ($ PER SF)	BITUMINOUS WEARING SURFACE ($ PER SF)
25 YEARS	2.0	11.56	14.29	0.44
DOUBLE PROTECTION	BITUMINOUS REMOVAL ($ PER SF)	CONCRETE DECK REMOVAL ($ PER SF)	CONCRETE DECK WITH EPOXY REBARS ($ PER SF)	WATERPROOF MEMBRANE W/ ASPHALT CVG ($ PER SF)
15 YEARS*	2.0	11.56	14.29	2.11
DOUBLE PROTECTION	BITUMINOUS REMOVAL ($ PER SF)	CONCRETE DECK REMOVAL ($ PER SF)	CONCRETE DECK WITH EPOXY REBARS ($ PER SF)	CONCRETE OVERLAY APPLICATION ($ PER SF)
20 YEARS*	2.0	11.56	14.29	4.77 (LOW SLUMP) 4.09 (LATEX-MODIFIED)

* WATERPROOF MEMBRANE W/ ASPHALT COVERING AND CONCRETE OVERLAYS REPLACED AT YEAR 15 AND YEAR 20, RESPECTIVELY.

5.9 EVALUATE FOR POSSIBLE BRIDGE REPLACEMENT

This alternative is self-explanatory and necessary when the overall bridge condition, not merely the bridge deck, is extremely bad, which makes rehabilitation very costly. Other reasons for choosing this option include:

- the bridge is too narrow to meet reasonable standards;
- the bridge type (through truss or girder, concrete beam and slab) can not be readily widened;
- the substructures are of questionable condition and load-carrying ability; and
- the replacement can be done without problems caused by external constraints.

Thus, the factors of overall bridge structural deficiency, functional adequacy, and safety must be considered to determine whether the entire bridge must be replaced and not simply the deck.

5.10 SUMMARY AND CONCLUSIONS

The problem of bridge deck deterioration has prompted extensive research into a number of protective systems, including concrete overlays, waterproof membranes, cathodic protection, and epoxy coated rebars. Each system has its own distinct advantages and disadvantages, service life, and cost characteristics. Additionally, the alternatives of doing nothing, performing only temporary repairs that essentially improve rideability, complete deck repair, and evaluation for

possible bridge replacement must be considered in developing rehabilitation/replacement strategies. The significant conclusions with regard to these alternatives include:

- The effectiveness of all protective systems is extremely dependent upon maintaining high design standards, proper construction practices, and quality control evaluations.

- Of the current and widely practiced protective systems, the use of cathodic protection is the most effective. This protection system is the only system capable of halting active corrosion. However, this protective system can not remove the existing material effects of corrosion - severe delaminations. Although highly promoted by the FHWA, unfamiliarity with the technology, high initial cost, and the requirement for continuous monitoring has limited the use of cathodic protection (26).

- Dense concrete overlays appear to be more effective than waterproof membranes, partly due to the tendency for waterproof membranes to blister (6).

- The performance and cost characteristics of the various deck rehabilitation and replacement alternatives must be maintained in an accurate and accessible data-base that can be used for deck repair and replacement strategy formulation.

- The advantages and disadvantages of the protective systems, the limitations with respect to deck geometry, and the special requirements associated with the protective

systems (e.g., electricity for cathodic protection) need to be captured into a decision matrix that allows for the technical evaluation of protective system alternatives. For example, waterproof membranes are not effective for grades in excess of 4 percent. Once this technical evaluation is completed, an economic evaluation of viable remaining alternatives can be carried out.

- The overwhelming choice of a deck protective system in the New England states is the waterproof membrane (99-103). However, it is important that this choice be based upon and justified by the results of a systematic approach or framework to the decision-making process involving deck repair/replacement alternatives. Such a systematic approach, that accounts for site-specific requirements (e.g., deck geometry and traffic volume), performance and life-cycle cost characteristics of alternatives, and socio/economic impacts of the surrounding area, is essential.

The next chapter will examine this systematic approach to decision-making in greater detail.

CHAPTER SIX

SYSTEMATIC APPROACH TO THE DECISION-MAKING PROCESS OF BRIDGE DECK REHABILITATION VERSUS REPLACEMENT

6.1 INTRODUCTION

The decision to rehabilitate or to replace a deteriorated bridge deck and its subsequent justification is a complex matter. As clearly delineated in Chapter One, bridge deck rehabilitation or replacement is consuming an increasing proportion of the resources of highway agencies. Also, the nature and extent of the deterioration are highly variable. This variability results from the fact that the deck condition is affected by many factors, to include: the age of the deck, the standards in use at the time of construction, the quality of the materials and workmanship, the type of design, and the service environment. Moreover, there is no single problem of bridge-deck durability and no single solution for the rehabilitation or replacement of all concrete deck slabs. Too often, a step-by-step analysis, which integrates the essential elements of reliable information, a well-defined criteria, clearly perceived constraints and uniform evaluation of technologically feasible alternatives, is not undertaken in this decision-making process. Instead, present policies for these decisions can be characterized as either:

- piecemeal synthesis, oriented toward emphasizing certain advantages of one alternative and underestimating its disadvantages, or

- decision matrices or flow diagrams based on a few parameters related to deck condition or service (42).

Thus, a comphrensive formulation of a decision-making system which will ultimately lead to rationally sound decisions and ensure the optimal or near optimal use of limited public funds is critical. Additionally, this systematic decision-making approach must allow for and encourage the use of experience, fiscal and engineering judgement, and the impact analyses of uncertainity and possible future decisions.

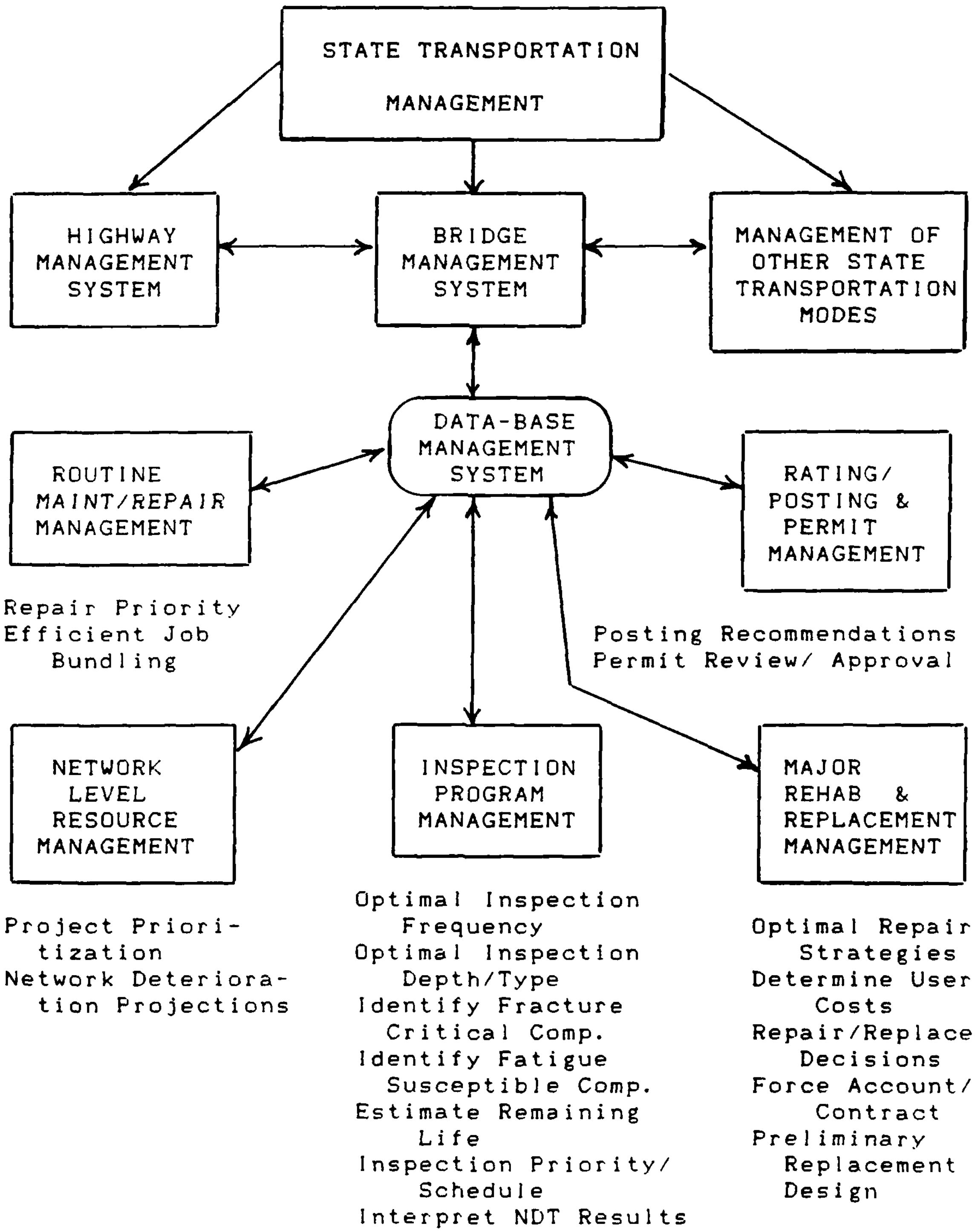
However, merely focusing on this deck repair/replacement decision-making process would be inappropriate. This process is but one component of an overall bridge management system. And the bridge management system is itself a component of an overall state transportation system and its related transportation programs (Figure 6-1). Thus, the purpose of this chapter includes the following:

- to outline briefly the strategic approach to developing state transportation programs,
- to outline briefly the concept of a bridge management system,
- to identify the components of a systematic repair/replacement decision-making process, and
- to outline the specific, logical steps or methodology associated with this decision-making process, and
- in the summary section, knowing the components and methodology, to provide the bridge engineer some suggestive

FIGURE 6-1

SCHEMATIC OF STATE TRANSPORTATION MANAGEMENT

AND BRIDGE MANAGEMENT SYSTEM



guidelines or steps to implement this process.

6.2 STRATEGIC APPROACH TO DEVELOPING STATE TRANSPORTATION PROGRAMS

As Figure 6-2 illustrates, the strategic approach to developing state transportation "programs" is a relatively straight-forward but complicated process. Furthermore, the actual implementation of this strategic approach is often haphazard or incomplete. The "programs" are essentially budgetary documents that allocate available funds for specific time periods and activities, such as inspection activities, routine maintenance, rehabilitation, new construction, and replacement. The essential steps of this process, as identified by Humphrey (48), are:

- Establishing statewide objectives and policies that incorporate and reflect structural condition, safety, service, social, economic and environmental goals.

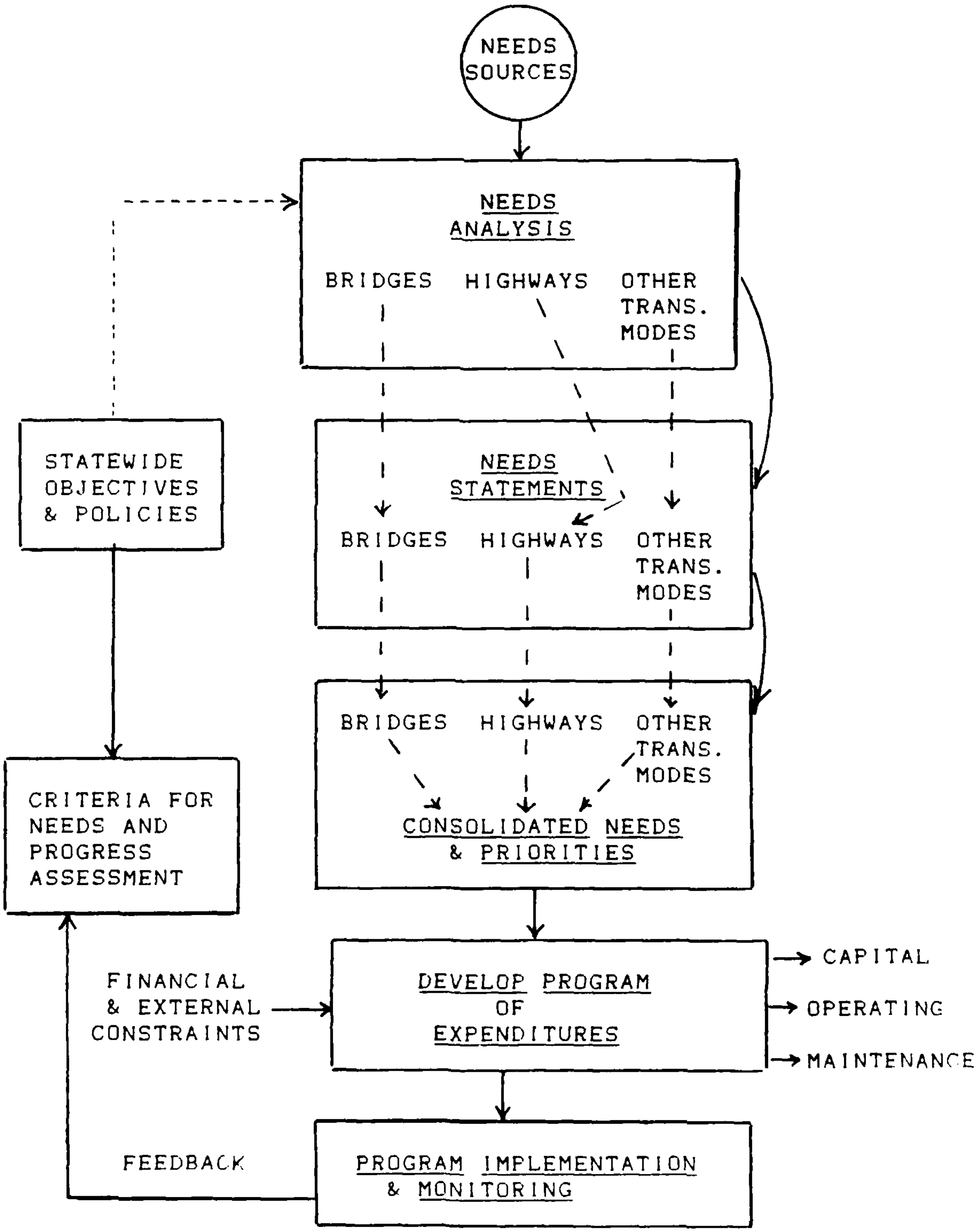
- Specifying transportation needs consistent with the criteria developed from the statewide objectives and policies. These needs consist of deficiencies in the various transportation systems and cost estimates for improvement.

- Formulating priorities, a rank ordering of projects using technical and non-technical, quantifiable and non-quantifiable factors, consistent with statewide objectives and policies and the developed need studies.

- Developing both fiscal and implementation programs for funding and execution of these capital, maintenance, and

FIGURE 6-2

STRATEGIC DEVELOPMENT OF STATE TRANSPORTATION PROGRAMS



operation projects. These programs must realistically incorporate financial, equipment, personnel, and technological constraints.

- Implementing these programs in the framework of budgets, schedules, and project milestones.

- Monitoring the programs and providing the necessary feedback.

Obviously, bridge projects, such as bridge deck repair and replacement projects, are simply a subset of the overall state transportation "program".

6.3 BRIDGE MANAGEMENT SYSTEM

The objective of the bridge management system is to "provide statewide standards and quality control with respect to implementing the most advanced technology to achieve the greatest cost-effectiveness in providing highway and bridge services" (58). Preliminary investigation of such a system using rule-based expert system concepts has already been performed by Seymour (90). Such a bridge management system, as illustrated in previous Figure 6-1, incorporating expert system concepts has many advantages (90):

- the system would provide a management tool for the maintenance, rehabilitation, replacement, prioritization, and fiscal planning for bridges.

- with respect to bridge decks, the system would allow the flexible integration of: current and future technological knowledge related to deck deterioration mechanisms, deck

condition assessment mechanisms, and available repair/ replacement alternatives; bridge management data-base files; functional adequacy, safety, fiscal and other criteria associated with statewide objectives and policies; and engineering judgement or the heuristic rules used by the expert bridge managers.

- the system will provide insight into the decision-making process by explaining the basis for conclusions.

- the system is amenable to modification as a result of new technological advances, new problem-solving techniques or models, new information, and additional engineering experience.

- the system is able to compensate for shortages in experience or the effects of personnel turnover.

Moreover, the application of a bridge management system, possibly enhanced by expert system procedures, would involve the following bridge maintenance management issues (90):

- Determination of the optimal inspection frequency, priority, and schedule for a structure,

- Establishment of the appropriate extent or depth of inspection for each structure,

- Identification of bridges with fracture critical elements and fatigue susceptible members,

- Selection of the appropriate destructive and non-destructive testing techniques for detailed inspections and subsequent analysis of the results,

- Evaluation of the extent, the techniques, and the

scheduling of routine maintenance operations,

- Evaluation of rehabilitation versus replacement decision-making for the entire bridge and its components,
- Selection of cost-effective repair technologies,
- Evaluation of "contract" versus "in-house" project assignments,
- Preparation of efficient work schedules and job bundling for inspections, maintenance, rehabilitation and replacement activities,
- Selection of the appropriate funding mechanisms and sources for a particular project or activity,
- Projection of future funding requirements and budget preparations consistent with resource constraints,
- Estimation of the remaining useful life of bridges and their components,
- Determination of the deterioration rates of overall bridge and its various components, and
- Effective and timely issuance of permits.

Thus, the decision-making process for repair versus replacement of deteriorated concrete bridge decks simply constitutes one item in this complicated bridge management system. Having briefly discussed the overall strategic approach to developing state transportation needs and the bridge management system, the focus will now shift to the repair versus replacement decision-making process for deteriorated concrete bridge decks.

6.4 COMPONENTS OF THE SYSTEMATIC DECISION-MAKING PROCESS

As previously mentioned, the systematic approach for the decision-making process can be described as a logical, clearly defined and step-by-step procedure. The key components of such an approach include the following (40,42,43):

- an objective,
- a data-base of pertinent information,
- a decision-making criteria,
- constraints, and
- a methodology for evaluation.

A clear definition of each item, as it relates to the bridge deck rehabilitation or replacement decision-making process, is critical.

6.4.1 OBJECTIVE

The objective of the systematic approach is to identify and initially prioritize bridge decks as possible rehabilitation/replacement candidates, identify all possible deck rehabilitation or replacement alternatives, evaluate these alternatives on the basis of clearly defined criteria and constraints, and arrive at an optimal or near optimal decision (40,42,43). With respect to bridge deck rehabilitation/replacement strategies, the various alternatives are summarized in Table 6-1. The ultimate aim of such a systematic approach is to discover those aspects or factors that truly influence the outcome of an optimal decision. But, in practical terms, the output is a prioritized deck project list

TABLE 6-1

SET OF DECK REPAIR/REPLACEMENT ALTERNATIVES

DO NOTHING

TEMPORARY REPAIRS INVOLVING PATCHING AND EPOXY INJECTIONS

DENSE CONCRETE OVERLAYS

WATERPROOF MEMBRANES AND BITUMINOUS WEARING COAT

CATHODIC PROTECTION

COMPLETE DECK REPLACEMENT

EVALUATION FOR POSSIBLE BRIDGE REPLACEMENT

and a forecast of funding needs over a specified time frame. These items, in turn, provide input to the overall bridge "program of expenditures" for the state.

6.4.2 DATA-BASE MANAGEMENT INFORMATION SYSTEM

A user-oriented, up-to-date, complete and orderly data-base is critical to the decision-making system. This data-base, which is closely linked to deck evaluation and is again illustrated in Figure 6-3, can be divided into the following sections (42,43):

- Structure Inventory and Traffic. The physical characteristics of the existing bridge, including its deck, and traffic-related information are stored in this section. This data can indicate the relative importance of the bridge to traffic flow, provide the physical requirements for a replacement alternative (for either the entire bridge or simply the deck) and assist in defining the estimates for rehabilitation alternatives. Table 6-2 provides a proposed listing of data-base items for this section.

- Bridge Inspection and Appraisal. Both general and detailed bridge inspection surveys reveal conditions of the superstructure, deck, and substructure. This stored data also reveals unsafe conditions, serviceability considerations, the estimated remaining life, and the extent of repairs required. Table 6-3 provides a listing of proposed items for this data-base section.

FIGURE 6-3

DATA-BASE ASSOCIATED WITH REPAIR/REPLACEMENT DECISION-MAKING SYSTEM

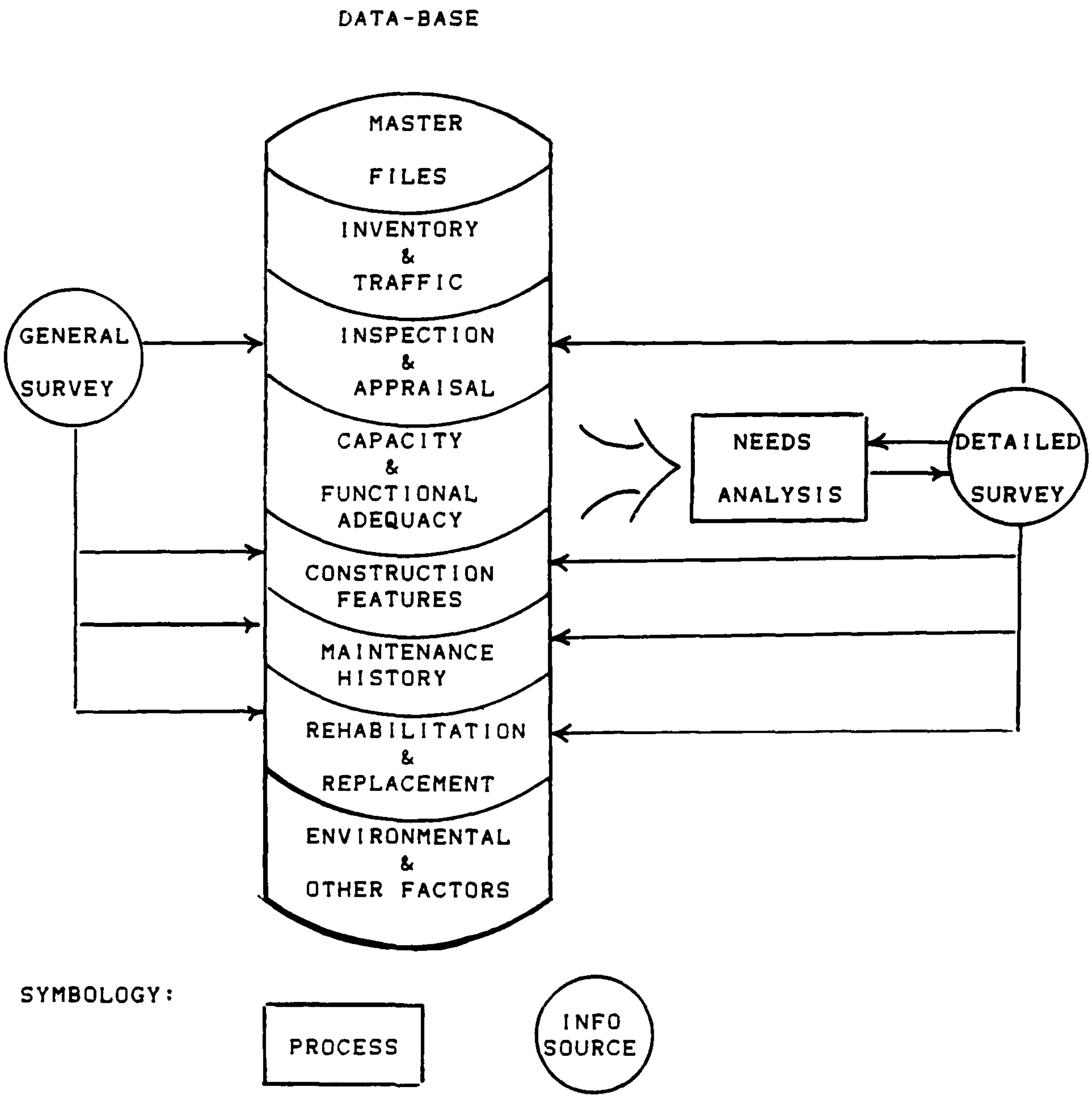


TABLE 6-2

STRUCTURE INVENTORY AND TRAFFIC DATA-BASE ITEMS

STRUCTURE INVENTORY & APPRAISAL SHEET

Revised 12-78

IDENTIFICATION

- State
- Hwy District
- County; City/Town
- Inventory Route; On ☐ Under ☐
- Features Intersected
- Facility Carried by Structure
- Structure No; 1 of
- Location
- Min. Vert. Clearance, Inv. Rte.
- Milepoint
- Road Section No
- Defense Bridge Description
- Defense Milepoint
- Defense Section Length
- Latitude
- Longitude
- Physical Vulnerability
- By pass, Detour Length
- Toll
- Custodian
- Owner
- FAP No

CLASSIFICATION

- Highway System
- Administrative
- Functional

	By	Date
Transfer of Data		
Maintenance Insp.		
Condition Analysis		
Appraisal		
Cost Estimate		
General Review		

STRUCTURE DATA

- Year Built
- Lanes on Str; under
- ADT; Year
- Design Load
- Appr Rdwy Width +Sh'ld
- Br Median ☐None ☐Open ☐Closed
- Skew
- Structure Flared ☐Yes ☐No
- Traffic Safety Features
- Navigation Control ☐Yes ☐No
- -Vertical ft
- -Horizontal ft
- Open, Posted, or Closed
- Type Service
- Structure Type-Main
- -Approach
- No of Spans-Main
- -Approach
- Total Horiz. Clearance ft
- Max Span Length ft
- Structure Length ft
- Sidewalk Lt ft, Rt ft
- Br Roadway Width (curb-curb) ft
- Deck Width (out-out) ft
- Vert Clearance over Deck ' "
- Underclearance-Vertical ' "
- -Lateral-Right ft
- -Left ft
- Wearing Surface

RECOMMENDED ADDITIONAL ITEMS:

PEAK HOUR TRAFFIC; YEAR

PROJECTED ADT; YEAR

HEAVY COMMERCIAL ADT; YEAR

DETOUR IMPACT ON TRAVEL TIME AND SPEED

JOINTS ON BRIDGE - TYPE AND LENGTH

LIGHTING SYSTEM

UTILITIES CARRIED; LOCATION

TABLE 6-3

STRUCTURE INSPECTION AND APPRAISAL DATA-BASE ITEMS

STRUCTURE INVENTORY & APPRAISAL SHEET

Revised 12-78

CONDITION	Material	Condition Analysis	Rating (0-9)
Deck			
Superstructure			
Substructure			
Channel & Channel Protection			
Culvert & Retaining walls			
Estimated Remaining Life		Approach Roadway Alignment	
Operating Rating		Inventory Rating	

RECOMMENDED ADDITIONAL ITEMS:

DEPTH OF COVER (INCHES)

DELAMINATED AREA (PERCENTAGE OF DECK AREA)

CHLORIDE CONTAMINATION (LBS/CY)

SPALLED AREA (PERCENTAGE OF DECK AREA)

CORROSION POTENTIAL (% DECK > -.35)

AGGREGATE REACTIVITY OR MOVING CRACKS (YES/NO)

SAFETY CONSIDERATIONS - UNSAFE OR HAZARDOUS CONDITIONS
(WIDTH, ALIGNMENT, LOAD-LIMITS,
STEEP GRADES, CLEARANCES, ETC.)

SERVICEABILITY - DRAINAGE
RIDEABILITY (ROUGHNESS COEFFICIENT)
LIGHTING

ESTIMATED REMAINING LIFE - OVERALL BRIDGE WITHOUT (WITH)
MAJOR REPAIRS
- DECK WITHOUT (WITH) MAJOR REPAIRS

- Structural Capacity and Functional Adequacy. The load carrying capacity of the bridge and its functional adequacy are stored in this data-base section. This information is especially helpful in appraising rehabilitation alternatives. A proposed item list for this section is in Table 6-4.

- Construction Features. Construction features associated with the bridge and its deck are stored in this section. Deck data would include concrete cover thickness, protective system employed, air entrainment characteristics, orientation and location of reinforcing steel, bituminous wearing surface characteristics, water-cement ratio, and other related factors.

- Maintenance History and Projected Future Needs. This stored data provides information on the major, or recurrent minor, maintenance and repair work accomplished in the past as well as projected future maintenance. This information is valuable in appraising the available rehabilitation alternatives.

- Rehabilitation and Replacement Characteristics. The details relevant to all rehabilitation and replacement alternatives, such as performance characteristics, service life, cost characteristics, availability of contractors or special equipment, and life-cycle activity profiles, are contained in this section.

- Environmental and Other Factors. In this section, major items of information, to include environmental impact statements, aesthetic considerations, developmental plans and

TABLE 6-4

STRUCTURAL CAPACITY AND FUNCTIONAL ADEQUACY

DATA-BASE ITEMS

STRUCTURE INVENTORY & APPRAISAL SHEET

Revised 12-78

APPRAISAL	Deficiencies	Rating 19__
Structural Condition		
Deck Geometry		
Underclearances-Vertical & Lateral		
Safe Load Capacity		
Waterway Adequacy		
Approach Roadway Alignment		

RECOMMENDED ADDITIONAL ITEMS:

ADEQUACY FOR PRESENT AND PROJECT TRAFFIC

LIMITS FOR SPECIAL PERMIT LOADS; WHEEL-LOAD CONFIGURATION USED

TABLE 6-5

MAINTENANCE HISTORY AND PROJECTED FUTURE NEEDS

DATA-BASE ITEMS

PROPOSED IMPROVEMENTS

Year Needed ______ Completed ______ Describe (item [illegible]) ______

Type of Service ______

Type of Work ______

Improvement Length ______ ft

Design Loading ______

Roadway Width ______ ft

Number of Lanes ______ Appr Rdwy Improvement - Year ______

ADT ______ Year ______ - Type ______

Remarks:

Cost of Improvements ______ $ ______ 000

Prel Engrg ______ $ ______ 000

Demolition ______ $ ______ 000

Substructure ______ $ ______ 000

Superstructure ______ $ ______ 000

Insp Date ______

RECOMMENDED ADDITIONAL ITEMS:

CHRONOLOGY AND BRIEF DESCRIPTION OF MAJOR REPAIRS DONE: (WHEN, WHAT, AT WHAT COST, CONTRACTOR, DESIGN SPECIFICATIONS, IMPROVEMENTS IN LIFE EXPECTANCY, ETC.)

BRIEF DESCRIPTION OF MINOR REPAIRS IN PAST FIVE YEARS

TABLE 6-6

ENVIRONMENTAL AND OTHER FACTORS

DATA-BASE ITEMS

AESTHETIC CONSIDERATIONS

DEVELOPMENTAL PLANS AND
PROJECTED NEEDS OF THE AREA SERVED

HISTORICAL SIGNIFICANCE

ACCIDENT STATISTICS

TABLE 6-7

REHABILITATION DATA-BASE ITEMS

ALTERNATIVE PROPOSALS FOR REHABILITATION

DESCRIPTION & DESIGN
SPECIFICATIONS

COST CHARACTERISTICS

SERVICE LIFE & IMPROVEMENTS
IN LIFE EXPECTANCY

PERFORMANCE CHARACTERISTICS

CONTRACTOR AVAILABILITY AND
LOCAL EXPERIENCE

SPECIAL EQUIPMENT AND
MATERIAL

TABLE 6-8

REPLACEMENT DATA-BASE ITEMS

ALTERNATE REPLACEMENT PROPOSALS

- DESCRIPTION & DESIGN SPECIFICATIONS
- COST CHARACTERISTICS
- SERVICE LIFE & IMPROVEMENTS IN LIFE EXPECTANCY
- PERFORMANCE CHARACTERISTICS
- CONTRACTOR AVAILABILITY AND LOCAL EXPERIENCE
- SPECIAL EQUIPMENT AND MATERIAL

PHYSICAL REQUIREMENTS OF PROPOSED BRIDGE STRUCTURE OR DECK

- ROADWAY WIDTH (CURB TO CURB)
- MINIMUM CLEARANCE
- TRAFFIC CAPACITY (PEAK HOUR)
- DESIGN LOADS
- ALIGNMENT
- RELATED STRUCTURES NEEDED
- APPROACHES
- UTILITIES TO BE CARRIED

SPECIAL FEATURES OF THE SITE (E.G., SUBSURFACE DATA)

DESIRED COMPLETION DATE

projected needs of the area served, the historical significance of the bridge, and accident statistics are stored.

As was clearly illustrated in the preceding data-base tables, the National Bridge Inventory information is an integral component of the overall data-base necessary for this deck repair/replacement decision-making process.

The importance of this data-base can not be underestimated. A bridge authority does not manage inspection, maintenance, repairs and replacement, but primarily manages the information from inspection, maintenance, repairs and replacement. Accordingly, the quality of the management is proportional to the quality of the data available or the information received. With respect to overall bridge management, the data-base information systems that contribute to the repair/replacement decision-making process also assist in the following bridge-related activities (53,57,58,64,74,86, 90):

- Establishing a standardized tool to predict "program" funding needs for bridges and related work on a network, county, district and statewide level,

- Promoting better decision-making with timely and credible information,

- Providing uniformity in the prioritization of maintenance, rehabilitation and reconstruction projects,

- Promoting more efficient use of technical bridge personnel,

- Standardizing and promoting efficiency in the inspection, evaluation, rating and posting of structures,

- Eliminating redundant and less efficient operating procedures,

- Placing greater emphasis on preventive and corrective maintenance practices, and

- Providing historical data such as expenditures and conditions on individual structures.

Thus, the data-base is a key component of the systematic approach to decision-making involving deck repair/replacement strategies.

6.4.3 DECISION-MAKING CRITERIA

Difficulties that are experienced in rehabilitation and replacement decision-making often result from a lack of an appropriate and clearly defined criteria for a comparative appraisal of competing alternatives. The most important criterion is adequacy, not only for the current use but also the projected future use, of the rehabilitated or replaced bridge deck (42,43). Without such adequacy, the choosen alternative is unrealistic. Moreover, developmental plans and projected future needs of the area served by the bridge influence this functional adequacy. For instance, such plans can change traffic patterns and thus influence both the type and frequency of bridge-crossing traffic (42). Inadequacy to sustain the projected traffic may require eliminating a economical rehabilitation alternative in favor of a more

complicated, more expensive deck replacement alternative or possibly an entirely new bridge. Other items that reflect on adequacy are the minimum requirements of horizontal and vertical clearances, roadway width, waterway openings, and safety (42). Basically, the bridge and its deck must meet these associated geometric standards. In additional to functional adequacy and minimum geometric standards as criteria for decision-making, the third criteria is an economic analysis involving present value, life-cycle costing for each alternative (42,43). There are a number of difficulties in applying such engineering economics. Although the initial direct costs can be predicted with reasonable accuracy, there are greater difficulties in predicting the appropriate discount rate, indirect costs, future maintenance costs, and future rehabilitation or replacement costs that may be part of the planning horizon of the bridge deck and the service life of the repair or replacement alternative.

6.4.4 DECISION-MAKING CONSTRAINTS

Another source of difficulty in the decision-making process is the lack of clear perception of all constraints. The most important constraint that affects this process is the availability and projected flow of funds (42,43,48). Not only must there be adequate funds for the initial investment but also for the future flow of funds that a particular rehabilitation or replacement alternative, if implemented, would require. Moreover, the factor of uncertainty prevails

in predicting these required future funds. Local and legal constraints can also affect the decision-making process (42,43,48). Involvement from local groups and consideration of their concerns can change what the decision-maker considers as the best decision. State laws or other legal requirements concerning items, such as minimum clearance, minimum load capacity, etc., may render changes in the decision-making process. Environmental reviews, peculiar site conditions, the historical value of a bridge, technological limitations, the local availability of specialized labor, material or equipment, and other factors could also influence the rehabilitation or replacement decision (42,43,48).

6.5 DECISION-MAKING AND PRIORITY PLANNING PROCESS

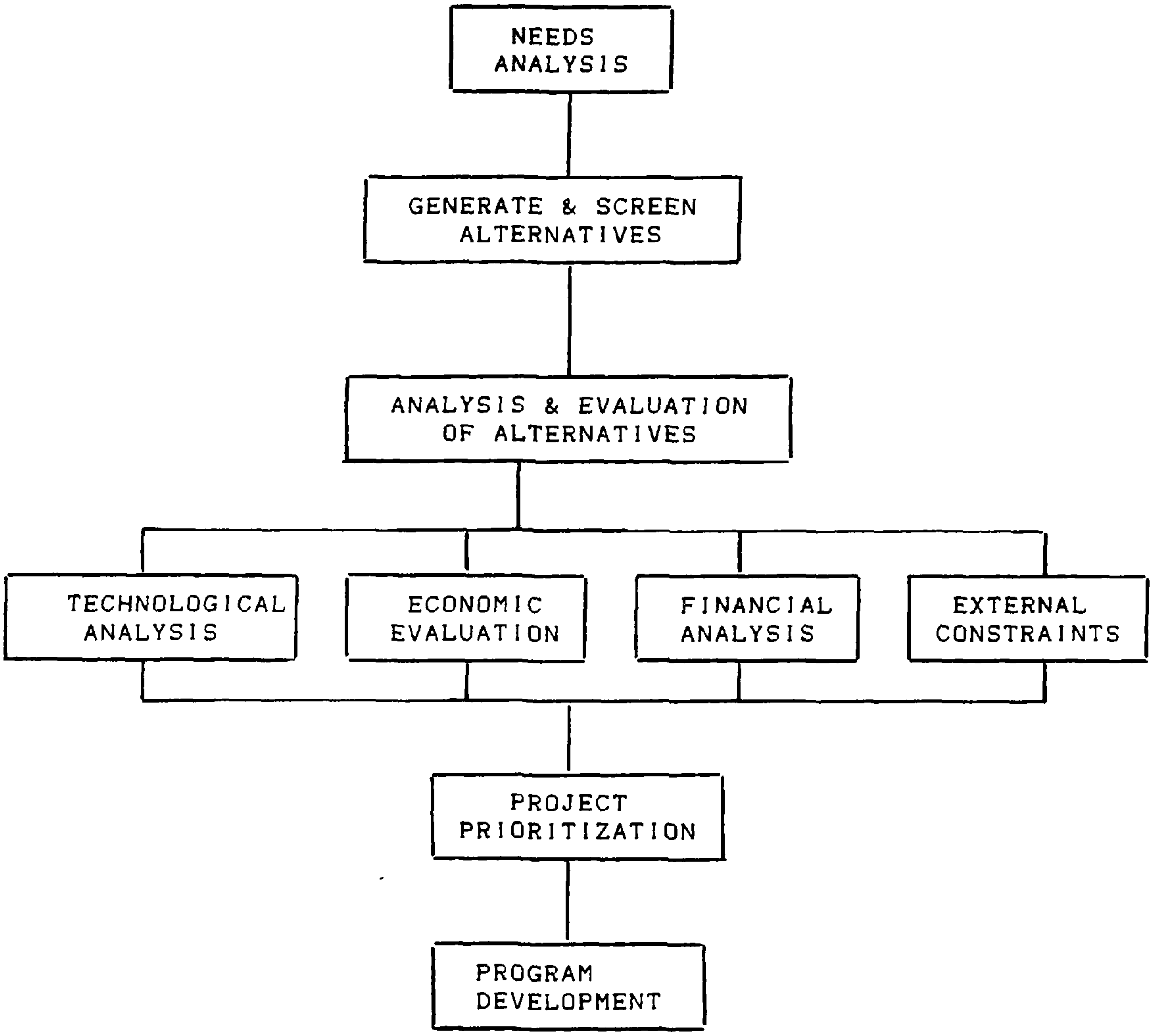
Having identified the key components associated with a systematic approach to the decision-making process, the specific, logical steps associated with this decision-making process must be outlined. These steps, illustrated in Figure 6-4, include (42,43,48,89):

- Needs analysis
- Generating and screening alternatives
- Analysis and evaluation of alternatives
    - -- Technological and adequacy analysis
    - -- Engineering economics evaluation
    - -- Financial constraint analysis
    - -- External constraints
- Project prioritization

FIGURE 6-4

KEY PROCESSES IN THE REPAIR/REPLACEMENT

DECISION-MAKING SYSTEM



- Program development

An understanding of these various steps is crucial in both representing and implementing the overall methodology associated with this decision-making process.

6.5.1 NEEDS ANALYSIS

The needs estimating process is an essential first step in developing some quantification of the nature and extent of the overall bridge or bridge deck deficiencies. This need analysis must be both reasonable and credible in order to evaluate the extent of resources required to meet these needs (42,43). Moreover, when needs analysis appears undisciplined or haphazard, funding priorities and implementation are often questioned by legislative bodies and taxpayers (48). During the needs analysis, a variety of tasks must be accomplished. These tasks include identification of potential projects, initial prioritization of these projects, and subsequent performance of detailed, preconstruction inspections. There are a number of sources for this identification of potential projects, to include (99-103):

- bridges located on proposed or approved highway pavement projects,
- bridges recommended for rehabilitation or replacement by general inspection personnel, routine maintenance personnel or regional offices,
- bridges that can be identified by the National Bridge Inventory data as structurally deficient, functionally obso-

lete, or requiring some sort of rehabilitative or replacement effort, and

- bridges that are the subject of public outcry as a result of numerous or tragic accidents, erratic or disturbingly slow traffic flow, and unacceptable rideability.

In a large number of states, to include the New England States, there is relatively little emphasis on the National Bridge Inventory data as a source for initial project identification (99-103). The primary sources are the highway pavement program and/or recommendations from regional offices and inspection or maintenance personnel. However, these primary sources do not necessarily insure that funds are being allocated in the most cost-effective manner to meet a state's most critical bridge needs. Thus, there must be a methodology developed that will identify and prioritize initial project selections.

The development of a method for identifying and prioritizing these initial projects must be done in the overall context of a complete bridge management system. Thus, bridge decks alone should not be the sole focus for consideration. Obviously, the condition of other bridge components, such as the substructure, must be incorporated into this project selection methodology. It may be more beneficial to rehabilitate the substructure of one bridge rather than rehabilitate the deck of another. Moreover, the sufficiency rating, which is associated with the NBI data and the FBRRP, does not

provide, by itself, an adequate method of addressing bridge needs over an extended period of time. In fact, as the Illinois DOT discovered, some of the bridges with critical needs may not be those bridges with the lowest sufficiency ratings (73). For instance, a bridge with a low substructure rating but in otherwise good condition and serving moderate traffic would not necessarily have a low sufficiency rating. Yet the improvement of this bridge is probably perferred over a bridge that is structurally sound but functionally obsolete with a low sufficiency rating and no history of accident experience. Nevertheless, development of a methodology linked to NBI data and other items in a bridge management information system appears to be a proper approach toward a logical, systematic criteria for determining bridge needs. Finally, this need analysis can not be confined to a single year period but must incorporate future forecasts of bridge needs.

The following methodology, taken largely from the Illinois DOT, should serve as an illustration of the needs analysis process (73): A starting point for their initial selection and prioritization process is the grouping of various bridges into four basic categories in order to examine their relative needs. These basic categories, which essentially define action thresholds, are:

1. Critical Backlog Projects - Structurally deficient bridges that are posted or on the verge of being posted for less than the legal load or closed. Need for improvement of

these bridges is immediate.

2. Other Backlog Projects - Bridges with structural deficiences or severe functional problems. These bridges can carry legal loads but must be monitored to avoid posting or closing.

3. Short-term Projects - Bridges with no immediate need for improvement, but expected to qualify within a five-year time frame.

4. Long-term Projects - Bridges with no immediate need for improvement, but expected to qualify in the five to ten-year time frame.

By canvassing the NBI data-base and developing bridge deterioration rates, bridges can be segregated into various mutually exclusive tables that constitute these various categories. These tables involve selected bridge items and the corresponding NBI ratings associated with these items. A summary of rating descriptions is contained in Table 6-9. The description of these mutually exclusive tables that follows is essentially for illustrative purposes. Each state would need to methodically develop their own tables, modifying both the items and condition criteria as appropriate for their individual statewide transportation policies and goals.

There are four data tables associated with the "critical backlog" category (Table 6-10). Table 1 contains those bridges having superstructure, substructure or culvert conditions with a rating of 3 or less. Table 2 contains those bridges

TABLE 6-9

NATIONAL BRIDGE INVENTORY RATING CONDITION CODES

Rating	Descriptions
N	Not applicable
9	New condition
8	Good condition - no repairs needed
7	Generally good condition - potential exists for minor maintenance
6	Fair condition - potential exists for major maintenance
5	Generally fair condition - potential exists for minor rehabilitation
4	Marginal condition - potential exists for major rehabilitation
3	Poor condition - repair or rehabilitation required immediately
2	Critical condition - the need for repair or rehabilitation is urgent. Facility should be closed until the indicated repair is complete.
1	Critical condition - facility is closed. Study should determine the feasibility for repair
0	Critical condition - facility is closed and is beyond repair

TABLE 6-10

CRITICAL BACKLOG CATEGORY

NEED	TABLE	ITEM	NBI #	CONDITION
SD	1	SUPERSTRUCTURE, SUBSTRUCTURE, OR CULVERT	59 60 62	≤ 3
SD	2	DECK	58	≤ 3
SD	3	STRUCTURAL CONDITION	67	≤ 2
FO	4	POSTED LOAD LIMIT	41	POSTED

TABLE 6-11

OTHER BACKLOG CATEGORY

NEED	TABLE	ITEM	NBI #	CONDITION
FO	5	DECK GEOMETRY	68	≤3*
SD	6	SUPERSTRUCTURE, SUBSTRUCTURE, OR CULVERT	59 60 62	= 4
FO	7	OPERATING RATING	64	< 27 T
FO	8	UNDERCLEARANCE	69	≤3
FO	9	APPROACH ALIGNMENT	72	≤3*

* ≥ 1000 ADT AND ACCIDENT EXPERIENCE

with a deck rating of 3 or less. Table 3 lists those bridges with an overall structure condition of 2 or less. Table 4 contains those bridges which currently have posted weight limits. Together, these tables constitute bridges whose need for improvement is immediate or the highest level. Thus, every effort should be made to evaluate these potential bridge projects and program them for some sort of action. However, this action could involve alternatives other than rehabilitation or replacement. For instance, the bridge may be closed to traffic when such closure is in the interest of public safety. Permanent closures should be considered when alternative routes are available. Additionally, the state highway agency may decide to recognize the deficiencies but do nothing. This procedure often involves state-maintained bridges serving field entrances, private entrances and extremely low volume roads. Application of these alternatives assures that no bridge in tnis "critical backlog" category is ignored. Moreover, all bridges in this category are not necessarily repaired or replaced in lieu of bridges which are of possible greater importance in another category.

There are four data tables associated with the "other backlog" category (Table 6-11). Table 5 includes bridges with a deck geometry of 3 or less for those bridges carrying 1,000 or more average daily traffic and having significant accident experience. Table 6 includes bridges with superstructure, substructure or culvert rating of 4. Table 7 includes bridges with operating ratings of less than 27 tons.

Table 8 includes bridges with underclearance ratings of 3 or less. Table 9 includes bridges where the approach alignment is 3 or less for those bridges carrying 1,000 or more average daily traffic and having significant accident experience. Significant accident experience is determined when a bridge contributes to high accident frequency for a specified period, such as two of the last three years. Bridges contained in the "other backlog" category are priority candidates for inclusion into a five-year program.

The "short term" project category constitutes those bridges that will likely deteriorate to the "backlog" condition within five years. There are five tables associated with this particular category (Table 6-12). Table 10 includes those bridges with a deck rating of 4 or 5. Table 11 includes those with a structural condition of 3 while table 12 includes those bridges with a superstructure, substructure, or culvert rating of 5. Table 13 contains those bridges with an operating rating of 27 to 35 tons. Finally, table 14 contains those bridges with a sufficiency rating of less than 50. The bridges classified within the "short term" category are discretionary candidates for inclusion in a five-year program.

The final "long term" category of bridges is defined by tables 15 through 17 (Table 6-13). This category, which contains the remaining identifiable needs, consists of bridges that are expected to deteriorate to the "backlog" category in 5 to 10 years. Table 15 includes bridges with an ADT greater

TABLE 6-12

SHORT TERM PROJECT CATEGORY

NEED	TABLE	ITEM	NBI #	CONDITION
SD	10	DECK	58	4 or 5
SD	11	STRUCTURAL CONDITION	67	= 3
SD	12	SUPERSTRUCTURE, SUBSTRUCTURE, OR CULVERT	59 60 62	= 5
FO	13	OPERATING RATING	64	27-35 T
FO	14	HBRRP RATING		< 50

TABLE 6-13

LONG TERM PROJECT CATEGORY

NEED*	TABLE	ITEM	NBI #	CONDITION
FO	15	DECK GEOMETRY	68	2*
SD	16	DECK	58	= 6
FO	17	HBRRP RATING		50-80

* $\geq$ 1000 ADT AND < 24 FEET DECK WIDTH
OR < 1000 ADT AND $\leq$3

or equal to 1,000 and having a roadway width of less than 24 feet or carrying an ADT less than 1,000 with a deck geometry of 3 or less. Table 16 includes those bridges with a deck rating of 6. The final table, table 17, includes the remaining bridges with sufficiency ratings of 50 to 80. Note that bridges in this "long term" category are not, by themselves, valid candidates for the five-year plan. Nevertheless, in Illinois these bridges sometimes are included as an essential part of a pavement improvement effort, which could include vertical and horizontal alignment adjustments, capacity improvements, safety and other improvements.

This illustrative process of categorizing bridges typifies a systematic approach to identifying candidate bridges and decks for rehabilitation or replacement. Such a process, tailored to the specific state and consistent with its objectives, permits monitoring of the progress of a bridge program, provides ready access to up-to-date reports, assures that the most critical needs are identified and met, and provides flexibility in the implementation strategy (73). For instance, one strategy may be to equalize progress made in retiring the needs in all four categories. Ultimately, a multi-year program could include a mix of projects from the various categories and thus address pavement needs, bridge needs, safety and urban traffic improvements. Of course, this needs analysis process is extremely dependent upon the quality of the data contained in the NBI. Therefore, extensive efforts to maintain the quality of this data are crucial.

AD-A169 697 PRELIMINARY INVESTIGATION OF THE SYSTEMATIC APPROACH TO THE REPAIR VERSUS..(U) ARMY MILITARY PERSONNEL CENTER ALEXANDRIA VA C W PROTASIO 26 JUN 86 3/3

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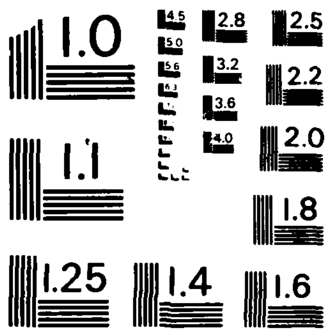


MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS - 1963 - A

Once a bridge or a bridge deck is selected as a candidate rehabilitation or replacement project, a high-quality, in-depth engineering bridge inspection is undertaken to establish a better condition assessment and obtain or verify supplemental data. Such supplemental data would include: highway design speed, traffic volumes, lane requirements, accident data, substandard features, and a load rating analysis (64).

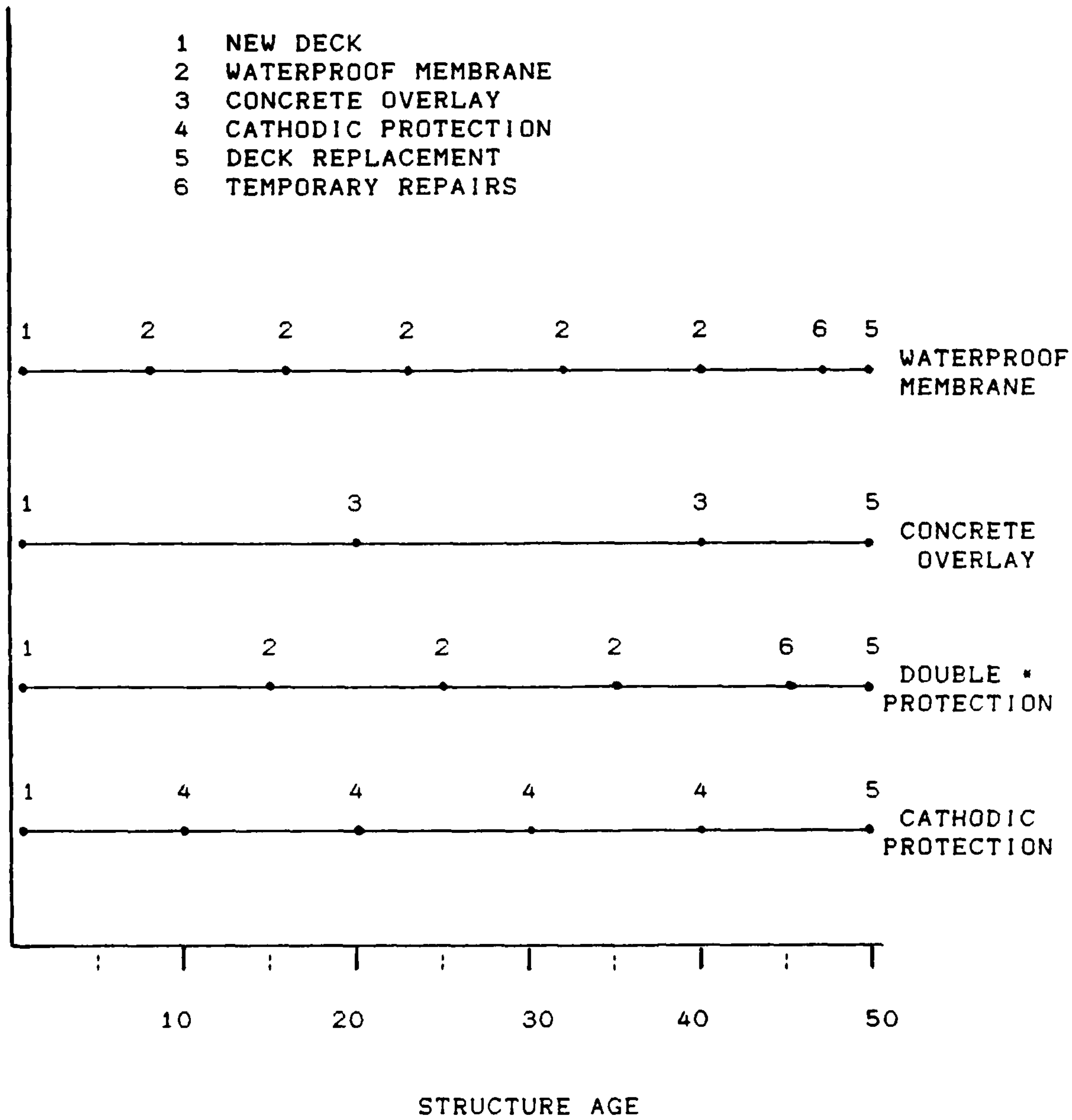
6.5.2 GENERATE AND SCREEN ALTERNATIVES

The next step in the decision-making process is generating and screening alternatives. The primary source of information associated with this step is the data contained in the "rehabilitation and replacement" data-base file. It is imperative that this file identify all available alternatives, to include performance characteristics, service life, and costs. Additionally, this data must continually be updated to reflect past experience (linking "inspection and appraisal" results with "maintenance history" and "construction feature" data-base files). Also, transportation research studies conducted by the state transportation agencies, the various universities, the FHWA, AASHTO, material suppliers, etc. must be reviewed to determine new rehabilitation or replacement alternatives or to modify the characteristics of existing ones. Ultimately a set of repair or replacement alternatives is developed. These widely used alternatives have been previously listed in Table 6-1.

An additional task associated with this step is the development of life-cycle activity profiles (49). These profiles reflect the tracks of future bridge repair or replacement activities common to a particular bridge deck. An illustration of such deck profiles is contained in Figure 6-5. This figure indicates that the replacement profile for a bridge deck is represented by a single activity profile. However, the repair profile is a combination (or splicing) of two profiles. The first profile provides the sequence of deck repair work from its current age to the end of its expected functional or useful life. The second profile, which is identical to the one selected under the replacement case, is added onto the first profile. Development of these profiles is based upon historical data-base files, such a "construction features", "maintenance history", and "rehabilitation and replacement" files. Ultimately, these profiles provide the basis for the subsequent economic evaluation of repair or replacement strategies. One final note is that this life-cycle activity profile concept can be applied not only to the deck but also to the entire bridge. Thus, as illustrated in Figure 6-6, life-cycle profiles can track future bridge repair activities common to a particular bridge structure type.

FIGURE 6-5

ILLUSTRATION OF DECK LIFE-CYCLE ACTIVITY PROFILES

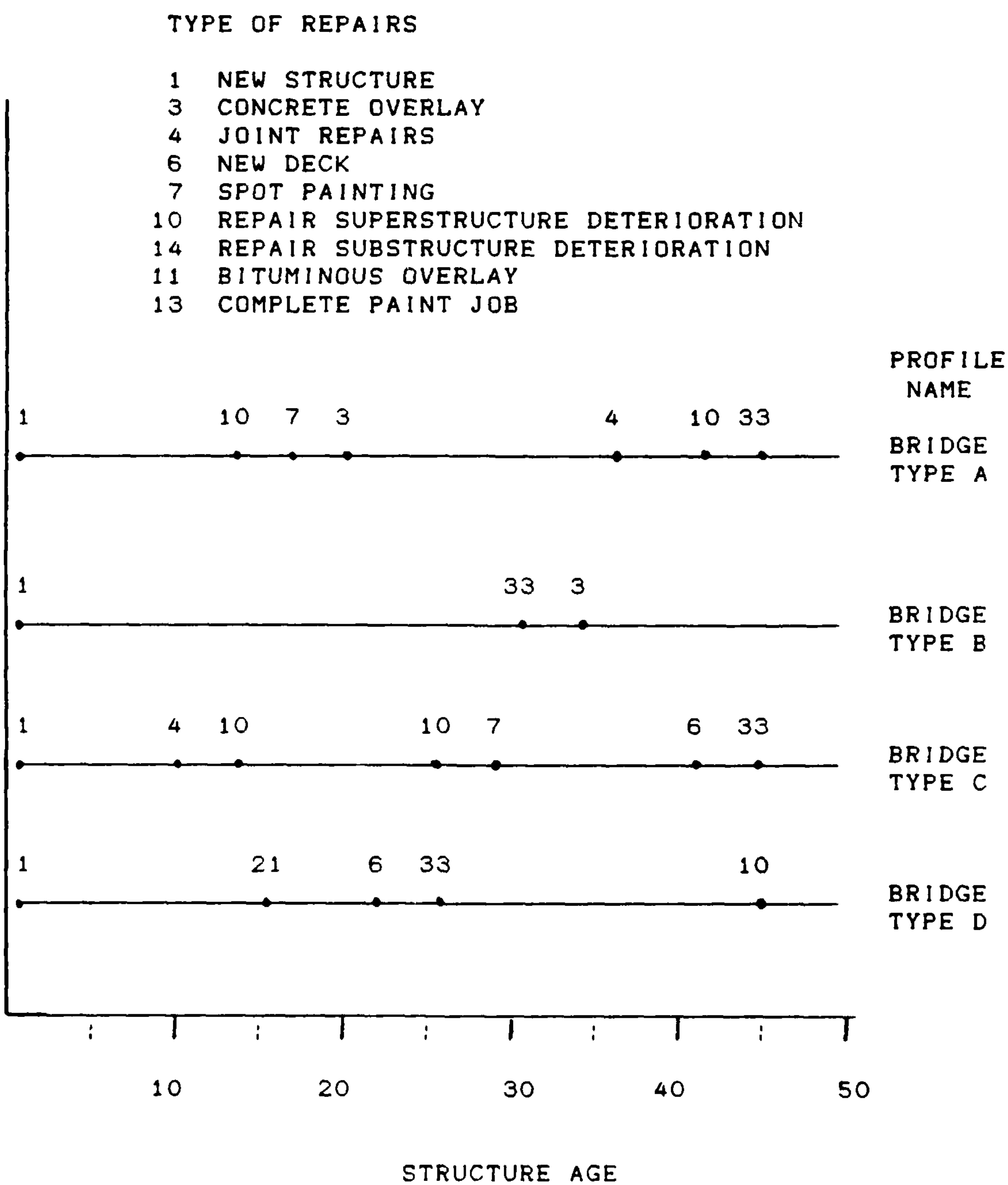


* EPOXY BARS AND WATERPROOF MEMBRANES

FIGURE 6-6

ILLUSTRATION OF BRIDGE

LIFE-CYCLE ACTIVITY PROFILES (49)



6.5.3 FACTORS AFFECTING SELECTION OF A REPAIR/REPLACEMENT STRATEGY

Prior to developing the next step, analysis and evaluation of the alternatives, some general factors that affect the selection of a repair/replacement strategy must be identified. Although the purpose of this thesis is to present a systematic approach to bridge-deck rehabilitation, the rehabilitation of the deck cannot be separated from an evaluation of the condition and load-carrying capacity of the remainder of the structure. If the bridge as a whole is found to be functionally obsolete (as a result of restrictions on width, clearances, alignment, and load limits), or if the bridge components exhibit deficiencies that limit the overall bridge service life, then the rehabilitation strategy must take into account the life of the whole structure (73). Basically, the factors that affect the selection of the appropriate strategy and the subsequent project prioritization include (70,106):

- the location of the bridge and its importance in the highway network,
- the volume of traffic at the bridge site and the impact of lane closures on traffic flow,
- the type, size, and geometry of the bridge,
- the nature and extent of the deterioration,
- the anticipated service life of the structure,
- the load-carrying capacity of the bridge,
- the cost of repairs or replacement and the availability of funds,

- the future reconstruction program, and
- the local experience and contractor expertise.

In the subsequent paragraphs, these factors will be considered and illuminated upon during the decision-making process.

6.6 ANALYSIS AND EVALUATION OF ALTERNATIVES

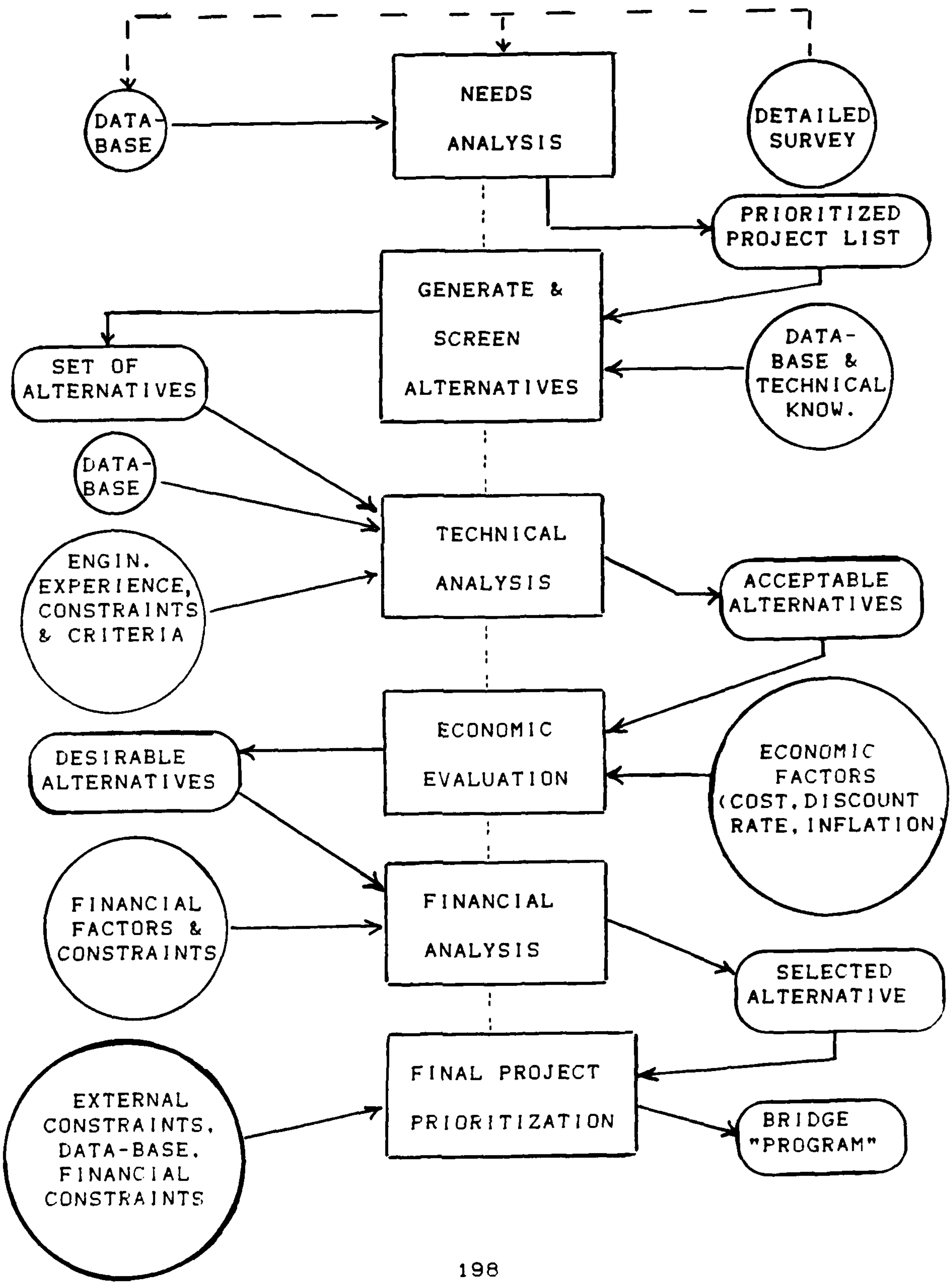
After initially identifying and prioritizing possible bridge deck candidates, conducting a detailed condition survey, and developing a set of useful repair or replacement alternatives, an analysis and evaluation of these deck replacement and repair alternatives must occur. This analysis and evaluation falls essentially into four categories: a technological analysis, an engineering economics evaluation, a financial constraint analysis and, finally, a consideration of social, economic, and environmental constraints. During the technological analysis process, the set of alternatives is analyzed with respect to adequacy and safety, the first and most important criteria. Additionally, the performance characteristics of each alternative and the physical factors or limitations (such as deck geometry, service life, load-carrying capacity, estimated remaining life, and the nature and extent of deterioration) related to the alternatives and the site are considered. Finally, engineering experience and judgement are incorporated into this technological analysis. In particular, a decision matrix can be developed to eliminate those alternatives that are not appropriate from a technological point of view. Here, the previous discussion

in Chapter Five of performance characteristics and advantages/disadvantages of repair/replacement alternatives is considered. The outcome is to obtain a set of acceptable, realistic alternatives, thus judiciously reducing the available alternatives.

Once this set of acceptable alternatives is determined, economic data (such as cost and service life of various repair/replacement alternatives, life-cycle activity profiles, and discount rates) are used in net present value (NPV) or equivalent uniform annual cashflow (EUAC) models to obtain the optimal or near optimal alternatives. These optimal or near optimal alternatives then undergo the financial analysis process, whereby financial factors and fiscal constraints are considered in the decision-making process. A final consideration is given to the external constraints, such as public pressure, the historical value of a bridge, the local availability of specialized labor, legal constraints, the environmental concerns, and the economic impacts on the surrounding community. These external constraints may subsequently alter the final choice of rehabilitation or replacement alternative for a particular bridge deck. A more detailed flow chart of the complete decision-making system is illustrated in Figure 6-7.

FIGURE 6-7

FLOW CHART OF THE DECISION-MAKING PROCESS (42)



6.6.1 TECHNOLOGICAL AND ADEQUACY ANALYSIS

A thorough technological analysis of the deck repair/replacement alternatives and physical consideration of the bridge, its deck, and the site is critical in determining acceptable alternatives. As previously mentioned, the first and most important criteria is adequacy and safety for current and projected <u>future</u> use of the deck and overall bridge structure. Adequacy and safety considerations involve the load-carrying capacity of the deck, the ability to meet current and future traffic demand, the appropriate deck width and alignment for stable traffic flow, and the elimination of safety hazards. Both adequacy and safety concerns must be met in order to establish the repair/replacement alternatives as realistic. As indicated previously, the developmental plans and the projected future needs of the area served by the bridge structure can change the traffic pattern and, thus, influence these functional adequacy and safety requirements.

Additionally, the choice of rehabilitation or replacement alternatives may be influenced by deck geometry or site limitations (70,106). Bridges with large skews, sharp tapers, or changing superelevation may exclude the use of finishing machines with transverse oscillating screeds. Thus, low-slump concrete overlays are impractical in these situations. Latex-modified concrete overlays are difficult to place on steep grades and crossfalls. Waterproofing membranes should

not be used on grades in excess of 4 percent or in areas subject to rapid acceleration, braking or turning movements. And, unless electrical power can be supplied to a bridge site or experimental solar-power provided, cathodic protection cannot be used.

The extent of deterioration is another important physical factor (70,106). For instance, if the bridge condition indicates unrepairable deterioration, such as cracking caused by reactive aggregates or severe frost damage, then deck replacement is the desired alternative. As another example, for severely deteriorated decks, the patching required prior to applying a waterproof membrane or cathodic protection is a major repair item and cost. In those instances of severely deteriorated decks with inadequate cover, the cover is still inadequate after patching. Therefore, concrete overlays are a more practical choice in that the areas of concrete removal do not require perimeter saw-cutting and the concrete is replaced as a function of applying the overlay.

The load-carrying capacity of the deck may be another important factor in analyzing repair/replacement alternatives (70,106). For those bridges that currently have or are on the verge of having a load restriction, the choice of rehabilitation alternative impacts dramatically on this functional adequacy criteria. Concrete overlays act as a structural component of the deck. In contrast, the bituminous overlays associated with waterproof membranes or cathodic

protection provide an additional and, often times, unacceptable load. Moreover, for those bridges having a load restriction even after rehabilitation, serious consideration should be given to deck replacement or possible evaluation for complete bridge replacement.

There are numerous other performance characteristics of various alternatives that may preclude their use (70,106). For instance, concrete overlays are normally not used when active cracks exist in the deck slab since these overlays are prone to reflection cracking. The quality of the concrete and the air void system must be evaluated prior to installing cathodic protection to ensure that the concrete will be sound following application. Bituminous overlays are permeable and allow increasing saturation of the underlying concrete. For concrete with inadequate air entrainment, this saturation may initiate deterioration. Also, where the deck surface was previously exposed concrete, the saturation may increase the frequency of freeze-thaw cycles. These advantages and disadvantages associated with the various repair and replacement alternatives have been summarized in numerous tables in Chapter Five.

The importance of a bridge may be determined by the traffic volume and the availability of alternate routes. Thus, an interstate bridge may warrant a higher standard of maintenance and priority for rehabilitation than a rural, low-volume bridge structure. Moreover, traffic volumes and the associated number and extent of lane closures may also

affect the choice of rehabilitation or replacement strategy. In some cases, the most expedient alternative may be choosen over a more technically desirable choice. This occurs frequently in highly populated areas, such as the urban area of Boston, where expedient repairs are choosen over replacement alternatives or more thorough rehabilitation alternatives.

Another physical consideration that impacts upon the selection of the appropriate repair/replacement alternative is the estimated remaining service life of the deck and/or of the entire bridge. For instance, if a bridge with a highly deteriorated deck has an estimated overall remaining life of 3 or less years, then consideration of replacing the entire bridge may need to occur. However, if the estimated remaining service life of the overall bridge is greater than 10 years, then deck replacement would likely be the preferred option. For a remaining bridge life of 4-10 years, a "do nothing" option, a temporary repair, complete deck replacement, and a bridge replacement may all have to be further analyzed in the decision-making process. Thus, many physical factors, such as the extent of deterioration, bridge geometry, the estimated service life of the bridge and its deck, the load-carrying capacity, the traffic volume and the impact of lane closures, must somehow be integrated into the decision-making process.

As previously stated, the solution to this dilemma of integrating these numerous technical, physical, site-specific factors revolves around the formulation of a complete bridge

management system. One use of this bridge management system would to be capture the performance characteristics of the various deck repair/replacement alternatives. Upon completion of the detailed condition survey of the bridge deck, the results and other data-base information could be analyzed using decision matrices, such as the one presented in Table 6-14 (70). This decision matrix (which would be transferred to a rule based expert system format) is developed so that, by the process of elimination, the identification of a least objectionable repair alternative occurs. In some cases, the matrix may eliminate all of the alternatives. When this occurs, one needs to work through the matrix again and, taking into account engineering judgement and cost estimates, examine the implications of violating each criterion in turn. As an example, the case of a deck with active cracks and with spalls and delamination over 5 percent of the deck area would exclude all the methods. However, in repeating the process, the choice could be between paying the high cost of patching the deck prior to applying cathodic protection or accepting the risk of limited service as a result of cracking in a concrete overlay. A possible alternative may be to combine more than one system. In the cited example, instead of patching the deck, the service life of the deck may be extended by applying a concrete overlay and then applying waterproofing and paving. The deck repair alternative(s) chosen from a technical point of view as acceptable and meeting adequacy criteria will ultimately be analyzed, along

TABLE 6-14

DECISION MATRIX INDICATING REPAIR METHODS

FOR EXCLUSION

CRITERION	CONCRETE OVERLAY	WATERPROOFING MEMBRANE W/ ASPHALT CVG.	CATHODIC PROTECTION
DELAMINATIONS & SPALLS > 5 % OF DECK AREA		NO	NO
CORROSION POTENTIALS > -.35 V OVER 20% OF DECK AREA		NO	
ACTIVE CRACKS IN DECK SLAB	NO		
REMAINING LIFE OF STRUCTURE < 10 YRS	NO		NO
CONCRETE NOT PROPERLY AIR ENTRAINED			NO
COMPLEX DECK GEOMETRY; SKEW > 50°; CURVATURE > 10°; CHANGING SUPER-ELEVATION	NO*		
LIMITED LOAD CAPACITY OR SPAN-TO-THICKNESS RATIO OF SLAB > 15		NO	NO
ELECTRICAL POWER UNAVAILABLE			NO
EPOXY INJECTION REPAIRS PREVIOUSLY PERFORMED AND NOT TO BE REMOVED			NO

* RESTRICTION APPLIES ONLY TO FINISHING MACHINES WHOSE AXIS OF SCREED IS TRANSVERSE TO THE AXIS OF ROADWAY

with the appropriate replacement alternative(s), on the basis of economic and financial factors.

6.6.2 ENGINEERING ECONOMIC EVALUATION

Economics is the science of evaluating cost and cost consequences associated with various types of expenditures. As is common in virtually all engineering problems, there are a number of mutually exclusive alternatives associated with remedying deteriorated bridge decks. Although the first important criterion is adequacy and safety, a cost-effective evaluation using engineering economics is the follow-on second criterion for a rational appraisal of acceptable alternatives. As a decision-making tool, engineering economics involves knowledge of several factors, including: the various costs and benefits of each alternative, the discount rate (time value of money), the service life associated with the alternatives, the planning horizon, and the mathematical models for actually conducting the evaluation. Essentially, there are four mathematical models or methods of economicaly analyzing alternative investment proposals (9,14,42,43,36):

- net present value (NPV),
- equivalent uniform annual cash flows (EUAC),
- prospective rate of return, and
- benefit-cost ratio.

Each method, if properly used and interpreted, will yield the same recommmendation as to the most cost-effective repair or replacement option among the technically feasible alternatives (36). As a result of the importance of this second

criterion, the next chapter will focus entirely on this engineering economic assessment procedure.

6.6.3 FINANCIAL CONSTRAINT ANALYSIS

Previously, the set of all possible repair/replacement alternatives had been narrowed to a set of acceptable alternatives, based upon adequacy and technological evaluation. During an engineering economic evaluation of these acceptable alternatives, the least cost repair and replacement alternatives are subsequently compared and, a supposedly optimal choice is obtained. However, this choice must then be analyzed with respect to financial constraints of available and projected flow of funds. Thus, this section will deal primarily with identifying the sources of funding, prevailing fiscal trends that impact upon funding, the need for establishing priorities, and the impact these financial constraints have on project implementation.

Funding for bridge deck rehabilitation or replacement is generated from three sources: federal, state, and local governments. Federal funding, primarily resulting from the Highway Trust Fund and the related Surface Transportation Assistance Act of 1982, consists of four categories of funds (57):

- Federal Critical Bridge Funds,
- Federal Aid Interstate Funds,
- Other Federal-aid System Funds, and

- Rail Highway Safety Funds.

The Federal Critical Bridge Funds are funds available for the rehabilitation or replacement of highway bridges meeting the following criteria (26,57,81): lengths of 20 feet or greater, classification of either structurally deficient or functionally obsolete, sufficiency ratings less than 80 for rehabilitation and less than 50 for replacement. Additionally, 15-35% of these funds must be utilized for bridges that are not on the federal-aid highway system. These funds are available at an 80% Federal and 20% State or local match. Finally, the proposed improvement must insure that the improved bridge will remain off the federal eligibility list for a substantial period of time.

Federal-aid Interstate Funds are funds available for bridge and roadway work on the Interstate system, including construction of new Interstate segments. These funds are available at a 90% Federal and 10% State match (57). Other Federal-aid System Funds include Federal-aid Primary, Federal-aid Secondary and Federal-aid Urban funds. These various funds are available at a 75% Federal and 25% State or local match for highway and bridge work on each of the respective federal-aid highway systems. Finally, Rail Highway Safety Funds are funds available at a 90% Federal and 10% State or local match for rail-highway crossing improvements (both bridge crossings and grade crossings). At least 50% of these funds must be spent on warning and protection devices at grade crossings (57).

At the state and local levels, the sources of funding normally involve highway user and property taxes, specific project-related bonds, and general fund appropriations for highway/bridge programs (48,57,85,106). State funding is normally allocated as State Maintenance Funds and State Bridge Bill Funds. The State Maintenance Funds are available for general bridge maintenance and to match federal funds, or can be used to fund 100% of state highway and bridge improvements undertaken as part of a Maintenance/Betterment Program. The state's share of the cost to rehabilitate or replace bridges longer than 20 feet is not to exceed $100,000. State Bridge Bill Funds are funds available for individual bridge projects specifically itemized in an approved capital budget. They may be used to match federal funds, or can be used to fund 100% of state projects. They also be used to match local funds for local projects or in combination with local funds to match federal funds for local projects. Local funding normally represents the local portion used to match federal and/or state funds for bridge improvement projects. These local funds normally represent either a percentage of the state's highway user taxes or are generated by locally enacted transportation-related taxes.

There are several fiscal trends that impact as constraints upon the funding of bridge deck repair/replacement projects. Among these trends are the following (14,39, 48,106):

- A growing gap between available funds and critical transportation needs has resulted in serious competition for transportation funds and increased pressure to use general revenue funds for transportation programs.

- Inflation has more than doubled the cost of construction and maintenance costs during the past 10 years. At the same time revenues, particularly those from motor fuel taxes, have not kept pace with rising costs.

- States have a substantial backlog of deferred maintenance, eventually implying greater reconstruction costs and higher user costs.

- Public scrutiny of transportation programs is increasing and different priorities can exist between the legislative branch, executive branch, and the general public.

- Transportation and bridge decisions and priorities are often dominated by a desire to maximize the use of available federal funds; however, as a result of the growing federal deficit, the extent of future federal funding has greater uncertainty.

As expected, both these fiscal trends and financial constraints can have an significant effect upon the choice of the appropriate bridge deck repair/ replacement alternative. Although technological, adequacy, and engineering economic analyses may indicate a particular bridge deck repair/ replacement alternative as optimal, the available and projected flow of funds may actually alter the decision. For instance, if the initial cost of the alternative exceeds the

available funds, then another alternative or a temporary repair may have to be enacted. Also, the requirement of a future flow of funds that an alternative is expected to create has to be considered in the decision-making process. Therefore, there is a need to continually evaluate all sources of funding, to include not only the current apportionment or allocation of funds but the projected or future forecast of funding or revenues. As a result of these financial constraints and trends, the need for a systematic approach to this deck repair versus replacement decision-making process becomes even more obvious. In practical terms, funding packages that incorporate both long-term and short-term project priorities and often times acceptable, rather than desirable, standards of adequacy, serviceability and safety must be developed.

6.6.4 EXTERNAL CONSTRAINTS

In addition to the financial constraints previously mentioned, there are also a number of other external constraints that ultimately impact upon the selection of the appropriate repair or replacement alternative. Among these constraints are:

- Involvement and consideration of the concerns of local groups,

- Legal constraints that require compliance with specified deck widths, horizontal and vertical clearances, alignments, barriers, etc. and legal constraints related to

environmental actions,

- Historical value of the bridge,
- Local availability of specialized labor, materials, or equipment,
- Peculiar site conditions,
- Environmental and energy concerns, and
- Planned and projected development of the area served.

As an example, local groups may insist upon a rehabilitation alternative that will keep traffic flowing rather than a replacement alternative that will effectively close the bridge to traffic and require a lengthy detour. In order to maintain the original design characteristics of a historical bridge, a rehabilition alternative may be required rather than a replacement alternative. In the absence of sufficient quantity of specialized labor or equipment, the concrete overlay rehabilitation or replacement alternative may not be feasible. The future development within the area served by the bridge may warrant a need to widen the bridge width to accommodate the changing traffic pattern and thus promote a deck replacement alternative over a rehabilitation one. Thus, as clearly is evident, consideration of external constraints is a part of the overall decision-making process involving deck repair/replacement strategies.

6.6.5 RESULTS OF ANALYSIS AND EVALUATION OF ALTERNATIVES

As a result of the complete analysis and evaluation of alternatives, the appropriate deck repair or replacement stra-

tegy can be formulated for a particular bridge or project. Not only has a decision been made as whether to repair or replace, but the specific technique to use and an estimated life-cylce cost has been ascertained. By repeating this process with respect to other projects identified in the needs analysis, the appropriate repair/replacement strategies can be formulated for a number of projects. The next step in the systematic decision-making process is to develop a final priority list of bridge projects. This project list can then serve as the basis for the eventual development of fiscal packages and a "program" or budgetary document for repair or replacement of bridge decks.

6.7 DEVELOPMENT OF PRIORITY LIST

The development of a final priority list of bridge deck projects is a complicated process that incorporates both quantifiable and nonquantifiable factors. When compiling this list, not only the deck but factors relating to the entire structure need to be considered in establishing priorities. Among the quantifiable factors are the structural condition and functional adequancy of the overall bridge, safety factors, and the essentiality to traffic (43). The structural condition and functional adequacy factors imply evaluation of the following:

- estimated remaining life of the structure and its deck,
- structural condition appraisal,

- the deck width,
- approaches and alignment,
- overclearances, and
- underclearances and waterway adequacy.

The factor of safety relates to the load-carrying capacity and an appraisal of accidents. The factor of essentiality to traffic relates to the current and projected traffic flow as measured by the average daily traffic (ADT) and peak hour traffic, the economic impact as measured by the area-tax base increase, the availability of alternative routes, and the type of road system that encompass the bridge. Additional quantifiable factors are the environmental and energy impacts, the user costs, the project cost, the cost of design alternatives (reducing design standards within an acceptable level of safety), and the source and availability of funds (both current and projected future amounts). Note that all of these quantifiable items have been identified as part of the previous evaluation of alternatives or can be identified using the available data-base files. Moreover, the impetus is now for the state transportation agency to develop some method of weighing these quantifiable factors to determine a project ranking. This method must be consistent with statewide objectives and policies. An illustration of such a priority-ranking methodology is contained in Tables 6-15 through 6-18 (43).

TABLE 6-15

BRIDGE REPAIR/REPLACEMENT PRIORITY RATING (43)

	NUMBER OF POINTS	
	INDIVIDUAL SUB-CATEGORY	CATEGORY RANGE
I. STRUCTURAL CONDITION & FUNCTIONAL ADEQUACY:		0-40
A. ESTIMATED REMAINING LIFE	0-5	
B. STRUCTURAL CONDITION APPRAISAL	0-15	
C. DECK WIDTH	0-5	
D. APPROACHES AND ALIGNMENT	0-5	
E. OVERCLEARANCES	0-5	
F. UNDERCLEARANCES OR WATERWAY ADEQUACY	0-5	
II. SAFETY:		0-25
A. SAFE LOAD CAPACITY	0-16	
B. SAFETY APPRAISAL (FREQUENCY & TYPE OF ACCIDENTS, % CORRECTIBLE, USER COMPLAINTS, POTENTIAL HAZARDS)	0-9	
III. ESSENTIALITY TO TRAFFIC:		0-35
A. TRAFFIC DEMAND (PRESENT & PROJECTED, PEAK HOUR TRAFFIC)	0-16	
B. AREA SERVED (PLANNED AND PROJECTED DEVELOPMENT)	0-8	
C. ALTERNATE ROUTE	0-8	
D. ROAD SYSTEM	0-3	
RATING		0-100

TABLE 6-16

STRUCTURAL CONDITION AND FUNCTIONAL ADEQUACY (43)

		RATING
A. ESTIMATED REMAINING LIFE "L"		0-5
$L > 20$ YEARS	0 POINT	
16 YEARS $\leq L \leq$ 20 YEARS	1 POINT	
11 YEARS $\leq L \leq$ 15 YEARS	2 POINTS	
6 YEARS $\leq L \leq$ 10 YEARS	4 POINTS	
$L \leq 5$ YEARS	5 POINTS	
B. STRUCTURAL CONDITION APPRAISAL		0-15
GOOD: MEETS PRESENT REQUIREMENTS	0 POINT	
FAIR: NEEDS MINOR IMPROVEMENTS TO MEET PRESENT REQUIREMENTS	5 POINTS	
FAIR TO POOR: DOES NOT MEET PRESENT REQUIREMENTS, NEEDS MAJOR IMPROVEMENTS TO MAINTAIN IN FULL SERVICE	10 POINTS	
POOR: DOES NOT MEET PRESENT REQUIREMENTS, NEEDS MAJOR IMPROVEMENTS TO MAINTAIN IN LIMITED SERVICE	15 POINTS	
C. DECK WIDTH		0-5
EXCEEDS DESIRABLE AASHTO RECOMMENDED REQUIREMENTS	0 POINT	
MEETS MINIMUM AASHTO RECOMMENDED REQUIREMENTS	1 POINT	
DOES NOT MEET MINIMUM REQUIREMENTS BUT CAN BROUGHT UP TO THESE REQUIREMENTS	3 POINTS	
DOES NOT MEET MINIMUM REQUIREMENTS AND CAN NOT BE REHABILITATED TO MEET MINIMUM REQUIREMENTS	5 POINTS	

TABLE 6-16

STRUCTURAL CONDITION AND FUNCTIONAL ADEQUACY (43)

(Continued)

		RATING
D. APPROACHES AND ALIGNMENT:		0-5
DO NOT ADVERSELY AFFECT TRAFFIC FLOW	0 POINT	
SLOW DOWN PEAK-HOUR TRAFFIC	1 POINT	
SLOW DOWN TRAFFIC FLOW AND AFFECT ADT	3 POINTS	
SLOW DOWN TRAFFIC , AFFECT ADT, AND CREATE TRAFFIC HAZARDS LEADING TO ACCIDENTS	5 POINTS	
E. OVERCLEARANCE (VERTICAL AND HORIZONTAL)		0-5
MEET DESIRABLE (EXCEEDS AASHTO MINIMUM) REQUIREMENTS	0 POINT	
MEET MINIMUM AASHTO REQUIREMENTS	1 POINTS	
DOES NOT MEET MINIMUM AASHTO REQUIREMENTS BUT CAN BE BROUGHT TO THIS STANDARD	3 POINTS	
DOES NOT AND CAN NOT BE BROUGHT UP TO AASHTO REQUIREMENTS	5 POINTS	
F. UNDERCLEARANCES & WATERWAY ADEQUACY		0-5
MEET DESIRABLE (EXCEEDS AASHTO MINIMUM UNDERCLEARANCE OR 100-YEAR FLOOD CAPACITY PLUS .30 M FREEBOARD) REQUIREMENTS	0 POINT	
MEET MINIMUM (AASHTO UNDERCLEARANCE OR 50-YEAR FLOOD CAPACITY WITH .30 M FREEBOARD) REQUIREMENTS	1 POINT	
DOES NOT MEET, BUT CAN BE BROUGHT UP TO ABOVE MINIMUM REQUIREMENTS	3 POINTS	
DOES NOT MEET AND CAN NOT BE BROUGHT UP TO ABOVE MINIMUM REQUIREMENTS	5 POINTS	

TABLE 6-17

SAFETY (43)

		RATING
A. SAFE LOAD CAPACITY (IN GROSS WEIGHT)		0-16
CLOSED TO TRAFFIC		16 POINTS

TWO AXLE VEHICLES	THREE AXLE VEHICLES	
3 TONS $\leq$ WL < 8 TONS	WL < 12 TONS	12-14 POINTS
8 TONS $\leq$ WL < 15 TONS	12 TONS $\leq$ WL < 18 TONS	8-11 POINTS
15 TONS $\leq$ WL < LEGAL	18 TONS $\leq$ WL < LEGAL	4-7 POINTS
LEGAL $\leq$ WL	LEGAL $\leq$ WL	0-3 POINTS

FOUR OR MORE AXLE VEHICLES	
WL < 12 TONS	12-14 POINTS
12 TONS $\leq$ WL < 27 TONS	8-11 POINTS
18 TONS $\leq$ WL < LEGAL	4-7 POINTS
LEGAL $\leq$ WL	0-3 POINTS

		RATING
B. SAFETY APPRAISAL		0-9
NO RECORDED ACCIDENTS/NO OBVIOUS HAZARDS	0 POINT	
ACCIDENTS WITH MINOR VEHICLE DAMAGE REPORTED; SOME HAZARDS NOTICED; HAZARDS AND CAUSES COMPLETELY CORRECTIBLE	2 POINTS	
ACCIDENTS WITH VEHICLE AND STRUCTURE DAMAGE, AND BODILY INJURY REPORTED; SOME HAZARDS NOTICED; HAZARDS AND CAUSES COMPLETELY CORRECTIBLE	4 POINTS	
ACCIDENTS WITH VEHICLE AND STRUCTURE DAMAGE, AND BODILY INJURY REPORTED; SOME HAZARDS NOTICED; HAZARDS AND CAUSES PARTIALLY ($\leq$ 50%) CORRECTIBLE	6 POINTS	
ACCIDENTS WITH VEHICLE AND STRUCTURE DAMAGE, AND BODILY INJURY REPORTED; SOME HAZARDS NOTICED; HAZARDS AND CAUSES ECONOMICALLY NOT FEASIBLE; WARRANTS REPLACEMENT	9 POINTS	

TABLE 6-18

ESSENTIALITY TO TRAFFIC (43)

			RATING
A.	TRAFFIC DEMAND		0-16
	WILL SATISFY PROJECTED (10-YEAR) ADT AND PEAK-HOUR TRAFFIC, WITH NO ADVESRSE EFFECT ON TRAFFIC FLOW	0 POINT	
	WILL SATISFY PROJECTED (10-YEAR) ADT AND PRESENT PEAK-HOUR TRAFFIC, WITH NO ADVESRSE EFFECT ON TRAFFIC FLOW	3 POINTS	
	SATISFIES PRESENT PEAK-HOUR TRAFFIC AND ADT, (PRESENT PEAK-HOUR TRAFFIC VOLUME/CAPACITY $\leq$1)	7 POINTS	
	SATISFIES PRESENT ADT, (PRESENT ADT VOLUME/ CAPACITY $\leq$1)	12 POINTS	
	DOES NOT SATISFY PRESENT ADT AND HAS ADVERSE EFFECT ON TRAFFIC FLOW	16 POINTS	
B.	AREA SERVED		0-8
	NO APPRECIABLE AREA TAX-BASE INCREASE (< 10% OF PRESENT TAX BASE) PROJECTED IN 10 YEARS	0 POINTS	
	MODERATE AREA TAX-BASE INCREASE (10 - 50% OF PRESENT TAX BASE) PROJECTED IN 10 YEARS	4 POINTS	
	CONSIDERAHBLE AREA TAX-BASE INCREASE (> 50% OF PRESENT TAX BASE) PROJECTED IN 10 YEARS	8 POINTS	
C.	AVAILABLE ALTERNATE ROUTE		0-8
	ALTERNATE NEWER OR BETTER DIRECT ACCESS TO BUSINESS DISTRICT OR COMMUNITY SERVED IS AVAILABLE; (ALTERNATE ROUTE LENGTH < 1.6 KM @ 32 KMH, OR < 4 KM @ 80 KMH)	0 POINT	
	ALTERNATE ACCESS TO BUSINESS DISTRICT OR COMMUNITY SERVED IS AVAILABLE; (ALTERNATE ROUTE LENGTH < 8 KM @ 32 KMH, OR < 20 KM @ 80 KMH)	4 POINTS	
	NO DIRECT ACCESS TO BUSINESS AREA OR COMMUNITY SERVED	8 POINTS	

TABLE 6-18

ESSENTIALITY TO TRAFFIC (43)

(CONTINUED)

		RATING
D.	ROAD SYSTEM	0-3
	NON-MUNICIPAL AND NON-COUNTY STATE-AID ROAD	1 POINT
	MUNICIPAL OR COUNTY STATE-AID ROAD	2 POINTS
	INTERSTATE OR STATE HIGHWAYS AND FEDERAL AID URBAN ROADS	3 POINTS

Despite the project ranking that may be obtained from considering these quantifiable factors, the nonquantifiable factors may have as great or even greater influence upon the final priority list. Among these factors are the following (42,43,48):

- commitments to citizens or community requests,
- public input, as demonstrated at public hearings, demonstrations or political elections or referendums,
- project readiness,
- emergency projects,
- equity considerations with regard to geographic allocation of funds,
- specific allocation of funds as part of a budget line-item,
- uncertainities related to the extent of future funding by various federal, state and local sources, and
- recommendations provided by state district engineers.

Although these factors are usually nonquantifiable, incorporating these items into process of establishing priorities is critical. To the extent that this occurs will vary from state to state. As a priority list is developed by committee at a state transportation agency, forwarded and reviewed by the State Transportation Executive, and finally submitted to the governor and legislature for further review and approval, each body will often times modify or change the importance of these nonquantifiable factors in the prioritization process. Nevertheless, some sort of balance must be established bet-

ween these quantifiable and nonquantifiable factors. The overall statewide transportation objectives and policies will impact upon this resulting balance.

The process of establishing a final priority list can be summarized as follows:

- initial priority list as part of the needs analysis whereby bridge projects are placed into four categories: critical backlog projects, other backlog projects, short-term projects, and long-term projects;

- project ranking within these four categories by the state transportation committee as a result of considering quantifiable factors;

- revision of project ranking as a result of considering non-quantifiable factors; and

- submission and recommendation of priority list of projects to the state transportation executive; subsequent modification and submission to the governor and legislative branch for consideration.

6.8 PROGRAM DEVELOPMENT

The "program" is a printed document made available to legislative bodies, state and local officials, and citizens that outlines the use of available funds for specified projects during a specified time period. By performing a needs analysis, evaluating alternatives and developing a list of priorities for backlog, short-term and long-term projects, the required funding levels needed to undertake these pro-

jects can be identified. As a result, the state can attempt to initiate funding packaages to meet these needs. Where funding resources are underestimated or will be constrained, changes in priorities are made or certain standards lowered to provide the minimum level of transportation services. By culminating in a "program" development, the systematic decision-making process has provided a methodology for rehabilitating or replacing deteriorated decks.

6.9 SUMMARY AND CONCLUSIONS

The decision to rehabilitate or to replace a deteriorated bridge deck is a complex matter. This chapter has outlined a framework for establishing a systematic approach to this decision-making process. It has also provided technical guidance on the quantitative methods that should be considered in the development of this approach. The major components of the process are:

- Establish clear objectives (identify possible deck rehabilitation/ replacement candidates, identify all possible deck repair or replacement alternatives, evaluate these alternatives on the basis of clearly defined criteria and constraints, and determine the optimal or near optimal decision; the practical output is a prioritized deck project list and a forecast of funding needs over a specified time frame),

- Establish a central data-base (user-oriented, up-to-date. complete data-base consisting of a structure inventory

and traffic file, a bridge inspection and appraisal file, a capacity and functional adequacy file, a construction features file, a maintenance history file, a rehabilitation and replacement file, and an environmental and other constraints file),

- Establish a decision-making criteria (functional adequacy, safety, and cost-effectiveness),

- Identify the decision-making constraints (availability of funds, local and legal constraints, environmental impacts, peculiar site conditions, historical value, etc.), and

- Develop a technical methodology (step-by-step procedures for performing the decision-making process).

The steps or components required to develop this technical methodology were subsequently identified as follows:

- needs analysis (identification of potential projects, initial prioritization of these projects, and performance of detailed, preconstruction surveys),

- generate and screen alternatives (maintaining thorough data-base file on all possible repair and replacement alternatives and developing life-cycle activity profiles for both the deck and the overall bridge structure),

- analysis and evaluation of alternatives (from a technological, economic, financial, and external constraint standpoint) in order to select the most optimal repair or replacement alternative and the associated life-cycle cost,

- final project prioritization (a prioritized listing of bridge projects and cost that can be used for developing

fiscal packages for implementation of these projects),

- program development (a printed document outlining the use of available funds for specified projects during a specified time frame).

Technical references are included together with some specific examples to assist in the development of a quantitative approach. Concurrent with the development of this systematic decision-making process, the following conclusions can be inferred:

- There is a need for each state to develop a bridge management program, preferably enhanced by expert system application, that would "provide statewide standards and quality control with respect to implementing the most advanced technology to achieve the greatest cost- effectiveness in providing highway and bridge services". Such a system is an invaluable management tool that can identify needs and bridge priorities for preventive and corrective maintenance, rehabilitation, and reconstruction.

- The decision-making process involving deteriorated bridge decks is simply one element of this overall bridge management program.

- The overall <u>decision-making process</u> methodology developed for deck repair/replacement can be applicable to other bridge-related components and other transportation decisions.

- The key to an effective bridge management program and a systematic decision-making process is a readilv-

available, accurate and complete data-base.

Although this chapter has discussed extensively the components and the framework for the deck repair versus replacement decision-making process, there is still a need to provide the bridge engineer with some suggestions or steps for implementing this process. The following are some suggestions on how to implement the techniques described.

- defining the statewide goals and policies concerning bridge management with a degree of clarity that allow for the development of specific criteria for evaluating deck rehabilitation and replacement projects;

- enhancing the available data-base by identifying and quantifying critical items necessary for a sound decision. As previously indicated in Chapter Four, innovative state transportation agencies, such as New York, New Mexico and Pennsylvania, have developed advanced and extensive bridge information data-bases and initiated effective computerized bridge management systems. In contrast, except for Maine, the New England states do not have an integrated transportation data-base management system in which bridge records are an important part (90);

- providing a simple, initial priority rating scheme whereby the bridge sufficiency rating is augmented by a few additional indicators which may include public, economic, and political importance as well as deck rating. Ideally, there is a need for mechanisms and methodologies that assess needs

and priorities in both the short-term and long-term time frame;

- accumulating a historical record of funds spend (for construction, maintenance, rehabilitation, and replacement) and of structural conditions by individual structure;

- developing life-cycle costing models that effectively measure the cost-effectiveness of competing alternatives;

- developing an expert system that captures the engineering judgement of bridge managers and the performance characteristics of various deck repair/replacement alternatives. This system can be used for both technological and adequacy evaluations of projects; and

- emphasizing and providing funding mechanisms to predict funding needs for :

a. appropriate corrective and preventive maintenance activities, and

b. appropriate rehabilitation and replacement activities.

These steps are essential for the eventual implementation of this decision-making process involving deteriorated bridge decks.

CHAPTER SEVEN

ENGINEERING ECONOMIC EVALUATION

7.1 INTRODUCTION

In the previous chapter, the engineering economic evaluation of competing deck repair and replacement alternatives was a critical process in the systematic approach to this decision-making dilemma. In many states, the present policies for the protection, rehabilitation and replacement of concrete bridge decks often consist of decision matrices or flow diagrams based on a few parameters related to the deck condition or service. As an example, the Ohio Department of Transportation has developed the following guidelines for bridge deck repair and replacement (81):

- If more than 25% of the deck area is deteriorated, overlay with Low-Slump High-Density Concrete or Latex Modified Concrete or replace the deck.

- If the deterioration area with spalls and delaminations is 25% or less, remove all the deteriorated concrete, patch the deteriorated area, and waterproof and overlay with 2 1/2 inch asphalt concrete.

- If no repairs are required, waterproof and overlay with 2 1/2 inch asphalt concrete.

In Vermont, the guidelines dictate deck replacement for decks with severe corrosion deterioration or actual holes covering 70% or more of the deck area, deck overlay for deterioration of 50-70% of the deck area, and deck repair for deterioration

TABLE 7-1

ACCEPTABLE RESTORATION PROCEDURES

FOR FEDERAL-AID PARTICIPATION (82)

CATEGORY	PROCEDURES	ACCEPTABLE PERMANENT RESTORATION	EXPERIMENTAL COST EFFECTIVE RESTORATION (Estimated Extended Life 10 to 15 years)
Structurally Inadequate		Complete Deck Replacement (Unless restorable)	
Extensive Deck Deterioration # 1	Required Restoration Work	Complete Deck Replacement	Removal of all deteriorated concrete. Follow the repair procedure* approved for the protective system selected.
	Testing	Steps #1 thru #5 as necessary Probably only Steps #1 & #2	Steps #1 & #2 only. (All steps on the first 5 plus 10% of the remaining decks)
	Suggested Protective Systems	Membrane w/ac overlay Two Course Iowa System or Latex Modified Concrete Cathodic Protection Epoxy Coated Rebars	Membrane w/ac overlay Cathodic Protection Iowa System or Latex Modified Concrete
Moderate Deck Deterioration # 2		Same as for Category #1 above OR Same as for Category #3 below as determined by the State	Same as for Category #1 above
Light Deck Deterioration # 3	Required Restoration Work	Removal and replacement of all areas of deterioration and chloride contaminated concrete as determined by corrosion potentials and/or chloride sampling. (Less than 5% of deck area)	Same as for Category #1 above NOTE: For this category of condition permanent restoration is strongly recommended.
	Testing	Steps #1 thru #5	Steps #1 & #2 only. (All steps on the first 5 plus 10% of the remaining decks)
	Suggested Protective Systems	Membrane w/ac overlay Cathodic Protection Iowa System Latex Modified Concrete	Membrane w/ac overlay Cathodic Protection Iowa System Latex Modified Concrete

TESTING STEPS:
1. Visual
2. Delamination
3. Electrical Potentials
4. Depth of Cover
5. Chloride Content

* (Park, 1980) (7).

less than 50% of the deck area. and for deck repair for less than 50% (99). In Maine. if 30% to 40% of the concrete below the top reinforcing is in poor condition, the entire deck is replaced (103). In Rhode Island. deck replacement is now considered when severe deterioration exceeds 25% of the total deck area (102). In New Hampshire, restoration procedures are compatible with the federal-aid guidelines in Table 7-1 (100). However, with such policies, the capacity to reflect the cost effectiveness of feasible alternative strategies is lacking. The enormous immensity of the nation's bridge deck deterioration problem, the continued growth of this problem, the staggering cost to repair or replace even the backlog of deteriorated decks. and the limitations on funding for most highway agencies imply the necesssity for cost-effective solutions. This cost-effectiveness analysis, in turn, implies a standardized methodology of comparison, whereby all of the costs incurred over the service life of the structure and the time value of money are considered (2,14,24,35). The objective is adopting the lowest life-cycle cost alternative that provides an acceptable service level. Therefore, this chapter will concisely outline the general methodology of applying engineering economics to this rehabilitation and replacement decision-making process, define the components of a life-cycle cost system, and present an illustrative mathematical model representing this economic process. The actual quantifying of costs, interest rates, deterioration rates, action threshold levels, service life, and planning horizons

into specifically tailored mathematical models is an area of future research beyond the present scope of this thesis.

7.2 PRELIMINARY OVERVIEW OF ECONOMIC ENGINEERING EVALUATION

As with the technical evaluation of repair/replacement alternatives, the effectiveness of an engineering economic evaluation is *extremely* dependent upon the accuracy and access to a comphrensive bridge management system data-base. The first step in determining the life-cycle costs for a given bridge deck is to ascertain the actual deck condition. This is accomplished as previously explained in Chapter Three, which dealt extensively with bridge deck evaluation. As a result of this deck conditon assessment, the decks can be divided into four broad categories (28,82):

- light deterioration,
- moderate deterioration,
- extensive deterioration, and
- structurally inadequate.

Also, the estimated remaining life of both the deck and the overall bridge structure, before replacement of each is required, must be determined. Once the extent of deterioration is known, there are essentially three restoration strategies available:

- Do nothing with eventual deck replacement.
- Rehabilitation of deteriorated decks followed by eventual replacement, and

- Replacement of the structure (deck) immediately.

The specific alternatives associated with deck rehabilitation or replacement, which were extensively discussed in Chapter Five, are again outlined in Table 7-2. After performing a technical analysis of these alternatives (outlined in Chapter Six), the remaining, technically-feasible, repair/replacement methods should then undergo an engineering economic analysis The replacement alternative is evaluated first because that alternative becomes an input parameter for the first two strategies. The recommended techniques for performing these economic evaluations are either equivalent uniform annual cashflows (EUAC) or a net present value (NPV) analysis (14,42,89). Although this chapter will focus on an illustrative EUAC technique, NPV can readily be obtained from the EUAC results. Moreover, for public highways, the NBI data indicates that over 3/4 of existing bridges were built prior to 1935 (1). Therefore, as a result of the long use of bridges and their decks (50 or more years), the choice of EUAC for perpetual service is recommended since, the difference between equivalent uniform annual cashflows for 50 years or more and for infinity (perpetual service) is small in comparison with the uncertainities of predicting future cash flows (14,24,36). Once the remaining restoration strategies are economically evaluated, a comparison is subsequently made to identify the most cost-effective solution.

TABLE 7-2

TECHNICALLY FEASIBLE ALTERNATIVES FOR BRIDGE DECKS

PROTECTION OF NEW OR REPLACEMENT DECKS	PROTECTION AND REHABILITATION OF EXISTING DECKS
Epoxy-coated rebars	Patching
Concrete overlays	Concrete overlays
Waterproof membranes with bituminous wearing course	Waterproof membranes with bituminous wearing course
Cathodic protection	Cathodic protection
Double protection (epoxy-coated rebars plus rigid overlay)	

7.3 COST AND OTHER COMPONENTS OF ENGINEERING ECONOMICS

In order to compare the various deck repair and replacement alternatives, a life-cycle costing method, such as EUAC, is needed. This method must incorporate the following key components: cost data associated with each alternative, discount and inflation rates, planning horizon of the structure (deck), and the service life of the various restoration alternatives. The cost data associated with the bridge deck rehabilitation/replacement decision-making process can be categorized as follows (14,89,90):

1. Force account routine maintenance and rehabilitation costs

    a. Maintenance overhead (equipment and facilities)

    b. Design cost (personnel plus overhead)

    c. Maintenance or rehabilitation work (field labor plus overhead, material and work contracted, and special equipment rental)

    d. Traffic maintenance and protection

    e. Road user costs, if appropriate

2. Contract routine maintenance and rehabilitation costs

    a. Design (personnel plus overhead)

    b. Contract administration

    c. Bid prices (labor plus overhead, materials, and equipment)

    d. Inspection costs (including overhead)

e. Traffic maintenance and protection

f. Road user costs, if appropriate

3. Initial (or replacement) cost items

a. Replacement structure cost, including the removal of the existing structure and approaches or connecting roadways, if necessary.

b. Contract administration and engineering design

c. User detour or delay costs

d. Annual maintenance, rehabilitation, and repair costs (including items previously mentioned).

e. Traffic maintenance and protection and road user costs, if appropriate.

4. Salvage value costs

5. Lost tolls or revenue due to closure or detours

6. Environmental and socio-economic impact costs

These costs will vary from state to state, will be site specific, will be dependent upon contractor and field force expertise and experience, and will fluctuate with time. Thus, there is a need to analyze each bridge deck as an individual case. However, in order to establish general policies, accurate and up-to-date cost data must be stored in accessible data-base files, such as the "construction features", "rehabilitation and replacement", and "maintenance history" files previously alluded to in Chapters Three and Six. Moreover, unlike the initial replacement or repair costs, many of the other types of costs, such as user costs,

environmental and social impact costs, are difficult to quantify. For instance, during deck replacement, the major economic user cost associated with the closed bridge is the cost of detouring vehicles around the obstruction. This cost includes additional vehicle-operating expenses, additional wages for paid drivers, and additional wear and tear on the detour routes themselves (57). Other concerns include delays in emergency service, rerouting school buses, and loss revenues in local businesses. Finally, all costs should be considered regardless of funding source. State officials often, but wrongly, adopt the view that project costs include only those costs that must be absorbed at the state and local levels (13).

7.3.1 DISCOUNT RATE AND INFLATION

In the engineering economic evaluation of alternatives, the discount rate is an expression of the time value of money (36). This discount rate is a function of the prevailing interest rate, the inflation rate, and the rate of increase in available funding (14). Historically, the interest rates used in engineering analysis of public works projects has been low as a result of investor safety due to the taxing power of the government (13). Moreover, classical engineering economics normally ignores the effects of inflation on the reasoning that this inflation affects all aspects of the cash flows in the same manner (2). Thus, the overall net effect on the decision-making process is negligible. But, the funds

for new construction, capital improvements, and maintenance of the nation's highways and bridges are derived primarily from motor fuel taxes (39,48,106). In periods of relatively low inflation, revenues normally increased with fuel consumption and funding kept pace with highway maintenance and improvement costs (14,39,48). However, in the late 1970's, rapid increases in the fuel costs resulted in reduction of fuel consumption and a corresponding reduction in the growth of revenues (14,48). Furthermore, high inflation increased highway and bridge-related improvement, rehabilitation, or replacement costs (14,48). A recent General Accounting Office (GAO) report to Congress indicated that highway and bridge construction and maintenance costs have increased at a rate approximately twice that of revenues since 1970 (13,48). Therefore, this period in the 1970's where inflation affected disbursements and receipts oppositely indicates that the effects of inflation should be considered in engineering economic analysis (14,48).

Although inflation and oil costs have been reduced in the recent 1980's, the inflation rate, nevertheless, should be incorporated into the true interest rate which is subsequently used in analyzing bridge deck repair/replacement strategy. As previously mentioned, the true interest rate or discount rate, i*, is a function of the prevailing interest rate, the inflation rate, and the rate of increase in available funding. This relationship is characterized in the following mathematical equation (14):

$$i^* = \{[(1+i)(1+q)]/(i+f) - 1$$

where i^* = true interest rate or discount rate,

i = prevailing interest rate,

f = the inflation rate, and

q = the rate of increase in funding.

For the period of 1970-1979, the values of f and q were as follows (14):

- inflation rate for highway or bridge construction costs of 9.4 percent,
- inflation rate for highway or bridge maintenance costs of 7.4 percent, and
- increase in funding for highway or bridge maintenance and construction of 4.8 percent.

As an example, using the above equation and assuming the prevailing interest rate was 10 percent for long-term public financing, a true interest rate, i^*, of 6.3 percent would be obtained. Thus, the impact of inflation and the rate of increase in available funding are important factors in determining the appropriate discount rate for use in an EUAC analysis.

7.3.2 PLANNING HORIZON AND SERVICE LIFE

Two significant and related elements in engineering economics are the planning horizon and service life. The planning horizon for a given bridge deck is the period of time from the present until the deck must be replaced or bridge use is abandoned, whichever comes first (13). The

maximum planning horizon for a bridge deck can be assumed to be 50 years (13,35,90). As mentioned previously, the difference between life-cycle costs, expressed as equivalent uniform annual costs, for periods longer than 50 years and for infinity (perpetual service) are not significantly different. Service life refers to the expected period of effectiveness of a particular action taken relative to protection, rehabilitation, or replacement of a bridge deck (13). Within the planning horizon, each alternative might entail several actions, each of which has an estimated service life. For example, a bridge with a planning horizon of 50 years and a serviceability strategy involving the application of waterproof membranes with a service life of 10 years implies five service-life cycles of the membrane system. The concept of life-cycle activity profiles, defined and illustrated in Chapter Six, are designed essentially to reflect this relationship between the planning horizon of a bridge deck and the service life associated with a rehabilitation or replacement technique. Having identified the important components of costs, discount rate, planning horizon and service life, an illustrative mathematical model (developed by Cady et al) used for an engineering economic analysis will now be presented (14).

7.4 MATHEMATICAL MODEL

Cost effectiveness implies a standardized comparison of cash flows incurred over the planning horizon of a structure

and considering the time value of money. Mathematical models, in the form of cash-flow diagrams and equivalent value equations, are thus developed to accommodate this comparison. Once the costs, discount rate, service life, planning horizon, and life-cycle activity profiles have been delineated, the engineering economic analysis involves the following (14):

- determining the equivalent uniform annual cashflows (EUAC) for the various technically-feasible replacement alternatives,

- determining the EUAC for the various technically-feasible rehabilitation alternatives,

- comparing the EUAC values of the various replacement alternatives and choosing the lowest cost,

- comparing the EUAC values of the various rehabilitation alternatives and choosing the lowest cost,

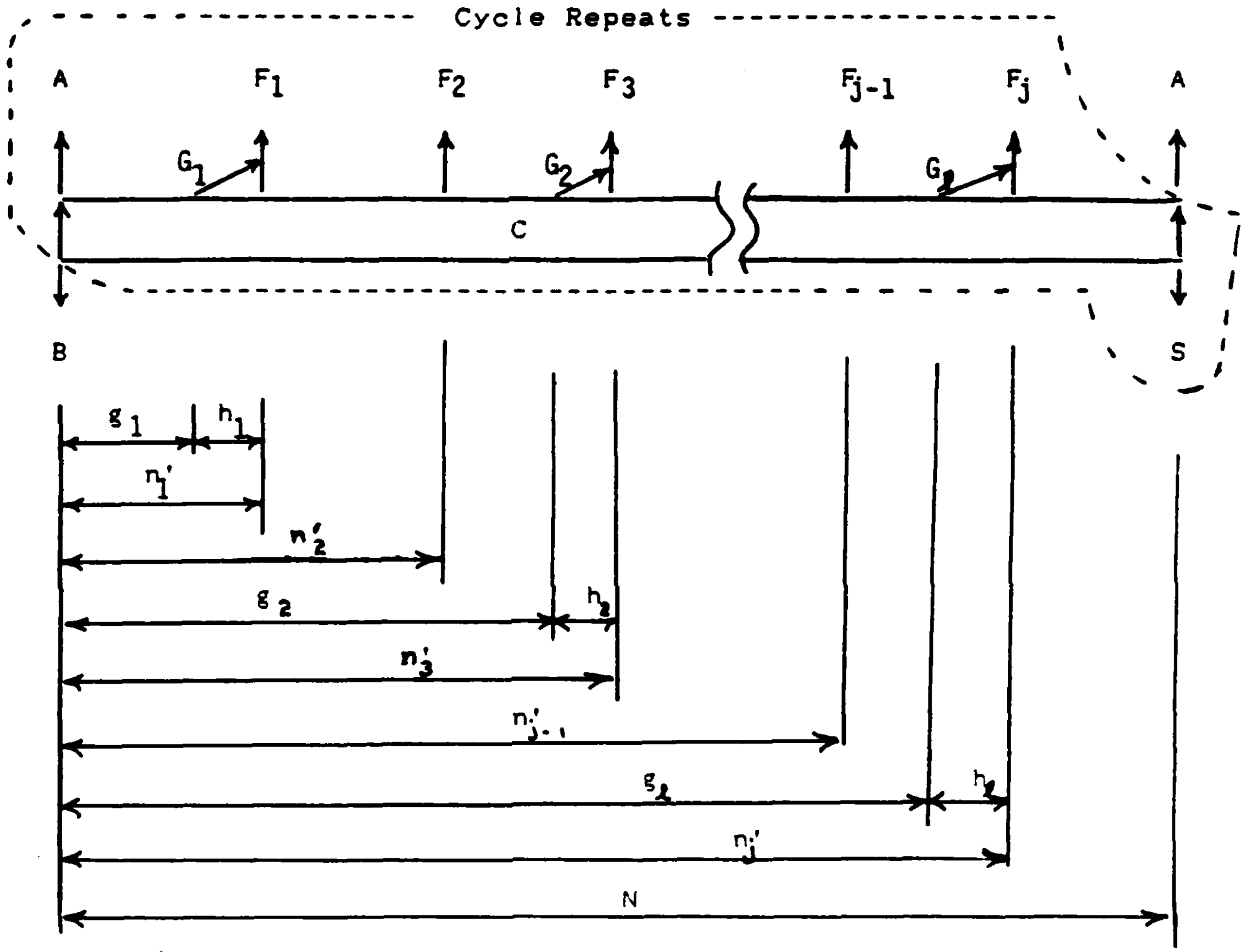
- comparing the lowest cost rehabilitation alternative with the lowest cost replacement alternative and calculating a value management term (VM); this term is obtained by subtracting the EUAC of the rehabilitation alternative from the EUAC of the replacement alternative, and

- making a decision based upon this value management term; a positive VM indicates rehabilitation and a negative VM indicates replacement; the magnitude of the VM term indicates the cost savings associated with the decision. Figures 7-1 and 7-2 outline the mathematical relationships and associated cash-flow diagrams for this illustrative model (14).

FIGURE 7-1

REPLACEMENT CASH-FLOW DIAGRAM,

MATHEMATICAL MODEL AND NOTATION (14)



$$\text{REPLACEMENT EUAC} = (A/P, i, N)\left[(A-S) + \sum_{m=1}^{\ell} G_m\,(P/G, i, h_m+1)(P/F, i, g_m-1) + \sum_{k=1}^{j} F_k\,(P/F, i, n_k')\right] + (S-B)(i) + C$$

where (A/P) = Capital recovery factor (A/P, i percent, n)

$= i(1+i)^n/[(1+i)^n - 1]$

(P/F) = Single payment present worth factor

(P/F, i percent, n) $= 1/(1+i)^n$

FIGURE 7-1

REPLACEMENT CASH-FLOW DIAGRAM,

MATHEMATICAL MODEL AND NOTATION

(Continued)

(P/G) = Gradient present worth factor (P/G,i,n)

$$= (1/i)\ (\{[(1+1)^n-1]/i(1+i)^n\}\ [n/(1+i)^n\ ])$$

A = Replacement structure (deck) first cost

B = Salvage value of present structure (deck)

S = Salvage value of replacement structure (deck)

C = Annual maintenance cost for structure (deck)

F = Single future expenditure (e.g., waterproof membrane)

N = Life of replacement structure (deck)

G = Annual increase in maintenance cost due to progressive deterioration

n' = Time to single future expenditure

g = Time to beginning of increasing maintenance costs due to progressive deterioration

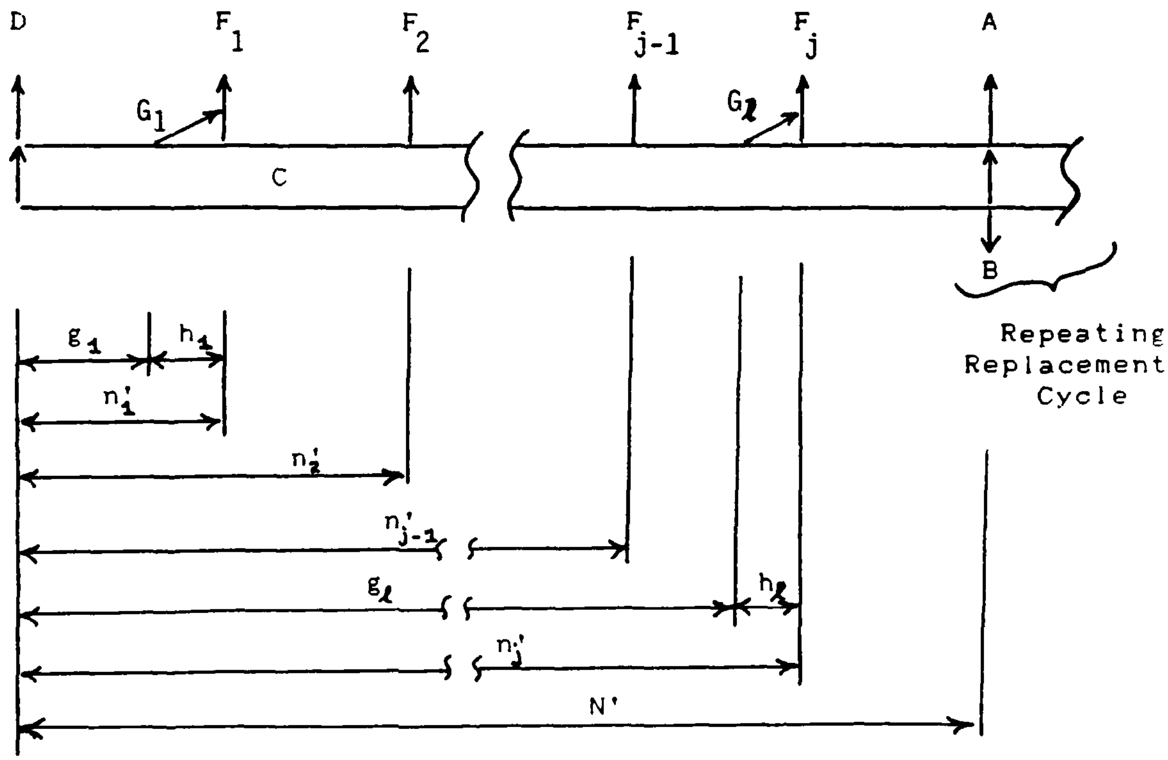
h = Duration of increasing maintenance costs due to progressive deterioration

i = Discount rate or i*

FIGURE 7-2

REHABILITATION CASH-FLOW DIAGRAM,

MATHEMATICAL MODEL AND NOTATION (14)



$$\text{Rehabilitation EUAC} = (\text{Replacement EUAC})(P/F, I, N') + (i)[D + C(P/A, i, N') + \sum_{m=1}^{\ell} G_m (P/G, i, h_m + 1)(P/F, i, g_m - 1) + \sum_{k=1}^{j} F_k (P/F, i, n'_k)]$$

where (A/P) = Capital recovery factor $(A/P$, i percent, $n)$

$= i(1+i)^n/[(1+i)^n - 1]$

(P/A) = uniform series present worth factor

$= (P/A, i, n) = 1/(A/P) = [(1+i)^n - 1]/i(1+i)^n$

FIGURE 7-2

REHABILITATION CASH-FLOW DIAGRAM,

MATHEMATICAL MODEL AND NOTATION

(Continued)

(P/F) = Single payment present worth factor

$(P/F, i \text{ percent}, n) = 1/(1+i)^n$

(P/G) = Gradient present worth factor (P/G,i,n)

$= (1/i)\ (\{[(1+1)^n - 1]/i(1+i)^n\}\ [n/(1+i)^n])$

D = Initial repair cost

N' = Time to require replacement

A = Replacement structure (deck) first cost

B = Salvage value of present structure (deck)

S = Salvage value of replacement structure (deck)

C = Annual maintenance cost for structure (deck)

F = Single future expenditure (e.g., waterproof membrane)

N = Life of replacement structure (deck)

G = Annual increase in maintenance cost due to progressive deterioration

n' = Time to single future expenditure

g = Time to beginning of increasing maintenance costs due to progressive deterioration

h = Duration of increasing maintenance costs due to progressive deterioration

i = discount rate or i*

Note that this model attempts to account for increases in annual maintenance costs as a result of increasing deterioration.

7.5 SUMMARY AND CONCLUSIONS

The overall objective of any bridge management system is to provide standards and quality control with respect to implementing the most advanced technology in order to achieve the greatest cost-effectiveness in providing bridge services. A key aspect of this bridge management system as applied to repair or replacement strategies for deteriorated bridge decks is the ability to perform an economic assessment of these strategies. Thus, this chapter provided a mathematical framework using equivalent uniform annual cashflows and generalized cash-flow diagrams as a means of comparison. Moreover, this comparison technique accounted for the parameters of cost, inflation rates, interest or discount rates, service life, planning horizons, and life-cycle activity profiles. This economic assessment is a critical portion of the systematic decision-making process.

Related to the concept of engineering economics, there are several conclusions that can be inferred:

- the majority, if not all, of the New England states make deck repair versus replacement decisions on the basis of guidelines that, at best, incorporate intuitive economic considerations. However, for an effective bridge management system, resolving the deck repair versus replacement dilemma

must include engineering economics.

- engineering economics implies the development of mathematical life-cycle cost models that will quantify cost data (initial, maintenance, rehabilitation, user, etc.) with respect to the economic principles of the time value of money and the effects of interest rates, inflation and funding. Thus, there is a need for a credible and accessible cost data-base.

- the results of engineering economics is not restricted to merely selecting the appropriate repair or replacement strategy. The results can contribute meaningfully in identifying the required funding associated with a needs analysis and in developing funding programs and workplans to meet these needs.

Thus, engineering economics can be applied to all facets of a bridge management system.

CHAPTER EIGHT

CONCLUSIONS AND RECOMMENDATIONS

8.1 INTRODUCTION

The purpose of this thesis was to provide a preliminary investigation into the systematic approach to the repair versus replacement decision-making process for deteriorated concrete decks. As Chapter One clearly indicated, the premature deterioration of concrete bridge decks is a major problem for transportation agencies in the Northeast. In this region, the factors of intense use, advancing age, frequency of overloads, extensive application of deicing salts, inadequate design and construction practices, and lack of periodic maintenance have contributed to the magnitude of this deterioration problem. In Chapter Two, the deterioration mechanisms of cracking, scaling, and spalling were identified and examined. These mechanisms provide a basis for developing deck inspection techniques, initial construction and restoration design standards, and data-base items that are an integral part of the deck repair/replacement dilemma and the subsequent decision-making process. Chapter Three identified the critical role of deck evaluation as the primary source of data in measuring the extent of deterioration, the remaining life of the deck and overall bridge structure, and the performance characteristics and service life of various construction and restoration techniques. Again, this data is a major component of the systematic decision-making process.

The focus of Chapter Four was the National Bridge Inventory and Inspection Program. Despite the need for inclusion of additional items, the NBI identifies critical inventory, condition, and appraisal inspection data items that have several bridge management applications, to include the repair/replacement decision-making process. Chapter Five examined in detail the application, performance, service life and cost characteristics associated with the various deck repair/replacement alternatives. Knowledge of these characteristics is the basis for the technical and economic evaluation of each deck restoration alternative assist in the decision-making process.

Chapter Six outlined the systematic approach to the deck repair/replacement decision-making process by identifying the components or general framework of the process and the logical steps or technical methodology necessary for process implementation. Although the focus of the decision-making process was specifically repair versus replacement of deteriorated decks, the concepts and methodology have application to other bridge management issues. Moreover, this decision-making process should be one element of a comphrensive and effective bridge management system. Finally, Chapter Seven discussed the concepts associated with the economic evaluation of competing repair and replacement alternatives.

6.2 CONCLUSIONS AND RECOMMENDATIONS

There are essentially three basic conclusions, previously identified in Chapter Six but worth repeating, that can be inferred from this study of the bridge deck repair versus replacement decision-making process:

- There is a need for state transportation agencies to develop a thorough, credible and accessible bridge management information system or data-base that is actively used in bridge management decisions. The benefits of this data-base include: enhanced ability to assure bridge safety; enhanced ability to prepare bridge maintenance work programs and bridge capital construction programs, including prioritizing projects; enhanced ability to formulate short- and long-range capital budget planning; enhanced ability to evaluate the load capacities of bridges; enhanced ability to route over-loaded vehicles; and the enhanced ability to evaluate new structure types.

- There is a need for state transportation agencies to develop a bridge management system that would "provide state-wide standards and quality control with respect to implementing the most advanced technology to achieve the greatest cost-effectiveness in providing highway and bridge services" Although some such systems often employ conventional, algorithmically based, application programs, a system employing rule-based expert system concepts as advocated by Seymour (90) provides greater flexibility. The use of an expert system allows for engineering judgement (in the form

of heuritic rules), provides an explanation of the reasoning used in formulating conclusions, and compensates for shortages in expertise or the effects of personnel turnover.

- The framework for the decision-making process, the components and methodology as explained in this thesis, have potential application for other bridge management issues beyond this repair/replacement dilemma.

8.3 Areas of Future Research

There are a number of areas where additional or future research is required in order to resolve the deck repair/replacement decision-making dilemma. These areas include:

- Further study into concrete deterioration mechanisms, especially in defining the conditions under which reinforcing steel will corrode. Another important and related area of concern expressed by the New England states is the apparent uncertainty of actual corrosion existence for chloride levels exceeding the FWHA threshold level. The importance of moisture and oxygen in this corrosion process must be quantified.

- Development of a nondestructive method or predictative model that will measure the rate of corrosion and not just the existence of this corrosion.

- Development of insitu techniques, such as infrared thermography and ground penetrating radar, that offer the possibility of rapid evaluation of the bridge deck condition, minimization of lane closure and the associated cost, and evaluation of asphalt-covered decks without extensive coring

or partial removal of the asphalt. The ability to identify the incipient or earliest stages of deteriortion is desired.

- Development of more accurate and objective interpretation techniques for the current deck assessment techniques.

- Continued study into the long-term performance of various protective systems, such as concrete overlays and waterproof membranes. Many of these protective systems represent relatively new technology that has been applied and studied on a small number of decks over a short period of time. The service life of these protective systems, performance, cost and application characteristics must be assessed. Additionally, the factors that influence their performance must be determined.

- Development of new materials (such as corrosion inhibitors for concrete), substitutes for deicing salts, new protective systems, improved construction methods, etc. must occur.

- Continued research into the deck repair/replacement decision-making process and the development of a bridge management system. Ideally, this would involve actually working with one or more state agencies to accomplishing the following:

a. defining the statewide goals and policies concerning bridge management with a degree of clarity that allow for the development of specific criteria for evaluating bridge maintenance, rehabilitation, and replacement projects;

b. development of a comprehensive, readily accessible bridge-management data-base, to include identification of critical data items and the values of these items;

c. development of life-cycle costing models that measure the cost-effectiveness of competing alternatives. Factors, such as cost data, discount rates, life-cycle activity profiles, and planning or service horizons, must be quantified.

d. development of an expert system that captures the engineering judgement of bridge managers and the known information on the performance characteristics of various protective systems. This expert system can then be used to conduct technological and adequacy evaluations of projects:

e. development of mechanisms and methodologies that assess needs and prioritize projects in both the short-term and the long-term time frame.

- Finally, the bridge management system concept must be expanded beyond deck repair/replacement decisions to incorporate other bridge management issues.

It is intended that this preliminary investigation (of the systematic approach to the decision-making process for repair versus replacement of deteriorated concrete bridge decks) serve as a basis for additional research and the ultimate development of a viable bridge management system within the New England states.

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